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OPTIMIZATION OF PROPANE ENGINES FOR LIGHT DUTY VEHICLES
- PHASE I -

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Optimization of Propane Engines for Light Duty Vehicles - Phase I -

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by
G. A. Lacy
R. C. Motta
T. R. Willsie
and others

Product and Development Engineering Department
Chrysler Canada Ltd.
Windsor, Ontario

March 1984

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PROJECT TEAM

The project team for Chrysler Canada Ltd. was composed of:

Mr. J.E. Elliot
Mr. B.E. Griffiths
Mr. G.A. Lacy
Mr. J.W. Lanigan
Mr. J.L. Mann
Mr. R.C. Motta
Mr. L.A. Robertson
Mr. T.R. Willsie

and others.

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	J. H. Morgan

17. Abstract

This investigation was conducted during the period of May 1982 through October 1983 to study current propane technology, and to identify opportunities for improvements.

Technical papers and texts were searched for all relevant propane material. This information, together with that gained from hardware manufacturers, experienced fleets, and other sources, was analyzed and condensed.

It is evident that present propane technology is significantly inferior to that of gasoline. Engine valve recession is the single most critical problem. Other major areas needing improvement include fuel efficiency, refueling techniques and hardware, and cold weather operating characteristics. The report also covers dual-fuel systems, fuel blends, engine lubrication, and fuel tank design.

The study recommends an R&D program to address these subjects. The suggested program is structured to permit doing some elements of it separately if desired. Included is an outline of suggested testing procedures, and recommended relative priorities.

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17. Résumé

La présente étude a duré de mai 1982 à octobre 1983 et avait pour but d'examiner la technologie actuelle de la carburation au propane et d'en cerner les possibilités d'amélioration.

Une recherche documentaire exhaustive a été faite en ce qui concerne l'alimentation des moteurs au propane. Cette documentation ainsi que les renseignements recueillis auprès des fabricants de systèmes au propane, des exploitants de parcs de tels véhicules, et d'autres sources, furent minutieusement analysés et condensés.

De toute évidence, la technologie actuelle des systèmes au propane est nettement moins évoluée que celle de la carburation classique. Le principal problème concerne l'érosion des soupapes du moteur. Les autres aspects nécessitant une amélioration comprennent la consommation, les techniques et les composants de ravitaillement, le fonctionnement par temps froid. Le rapport traite également des systèmes bi-carburant, de la composition des carburants gazeux, de la lubrification du moteur et de la conception des réservoirs.

L'étude préconise un programme de R&D structuré, de façon que certains de ses éléments puissent être réalisés séparément s'il le faut. Elle présente un aperçu des essais envisagés et l'ordre des priorités préconisé.

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FOREWORD

The Federal Government of Canada has established a National Energy Program directed at achieving energy independence for Canada. The primary goal is to be self-sufficient in oil by 1990. An important element of the program is to reduce the need for petroleum-based fuels by promoting the use of alternative fuels such as natural gas and propane. In order to achieve this goal, it is necessary to identify factors that impede maximum utilization of these alternative energy sources and to take steps to alleviate or eliminate them.

This study is the first phase of a program undertaken to identify those factors which relate to propane engines and fuel system components by reviewing current propane technology, identifying opportunities for improvements, and defining an R&D program aimed at optimizing propane engines and fuel system components.

EXECUTIVE SUMMARY

Propane is an under-utilized motor fuel that is an excellent alternative to gasoline provided there continues to be an economic incentive for its use. This study was undertaken to define current state-of-the-art propane technology, identify opportunities for improvements, and to define an R&D program aimed at optimization of propane engines and fuel system components.

Presently available propane conversions are subject to many limitations. The level of sophistication of after-market conversions is dictated by economic factors and available hardware. The high exhaust valve seat wear that occurs on gasoline cylinder heads when they are used with gaseous fuels results in early head failures. As a result of these and other factors, the overall quality and performance of vehicles converted from gasoline to propane varies widely.

The spark ignition engine as we know it today has evolved hand in hand with gasoline fuels. Neither the engine nor the fuel can be considered in isolation; the properties of one are dependent on the other. As a result, the engine must be modified or redesigned if optimum results are to be obtained with any alternative fuel. The buyer will inevitably compare a propane vehicle with its gasoline counterpart and, in addition to substantial fuel cost savings, will expect comparable durability, performance, driveability, and convenience. These objectives are best achieved through R&D at the OEM level to produce truly competitive propane vehicles. An overview of some of the necessary considerations follows:

Compression Ratio

There are significant benefits available for propane engines in the areas of both fuel economy and power output through higher compression ratios. In practice, however, these benefits are limited by manufacturing considerations, engine component reliability, and by the risk of spark knock or detonation (as described in more detail in the ignition section below). Propane does not behave in the same manner as gasoline with respect to knock, and experience gained with gasoline octane ratings should not be used to predict the knock resistance of propane at other compression ratios. Development is required for each engine design to clarify this relationship and to define the practical limit for increased compression ratio.

Carburetion

A propane engine can tolerate much greater variations from the ideal fuel mixture (both richer and leaner) than the equivalent gasoline engine without serious driveability problems. As a result, relatively simple propane carburetors have been successful in the sense that owners have

been generally satisfied with their operation. They are far from optimum in regard to fuel economy, power output, and driveability. Improved carburetion would achieve these objectives through better calibration of fuel-air ratio, with power enrichment, leaner cruise mixtures, and perhaps some degree of fuel shutoff during deceleration. Contrary to popular belief, good cylinder-to-cylinder fuel distribution is not ensured simply because propane is metered as a gas. In fact, testing indicates that it may be no better than with gasoline except during warmup and low manifold flow rate conditions. It should be possible to gain fuel economy through leaner overall mixtures by improving the homogeneity of the mixture leaving the carburetor. A major effort is required to develop improved carburetor designs, and to quantify the available benefits. Without this stimulus, it is unlikely that carburetion technology will advance at the rate at which this development is desirable.

Ignition

The combustion characteristics of propane and gasoline are significantly different in the area of ignition delay and flame speed. Since spark advance is primarily determined by these two factors, it follows that spark timing requirements are also different. The anti-knock quality of propane is also of particular concern because its relationship to engine speed differs from that of gasoline. Spark knock in a gasoline engine normally occurs at relatively low engine speeds, where it is clearly audible and usually results in correction before damage occurs. Spark knock in a propane engine is usually encountered at higher engine speeds where other noises tend to mask the sound, with potentially disastrous results. The common aftermarket practice of advancing the timing at low engine speeds and retarding it at high speeds may needlessly erode power output in some cases, while in others it may not provide adequate protection against spark knock. Spark timing development must be done on an engine dynamometer with careful attention to avoiding knock on the lowest octane fuel likely to be encountered.

Other widely accepted beliefs regarding propane spark plug voltage, energy, and heat range requirements also appear to be suspect. It is not possible to separate the effects of ignition timing on plug voltage requirements because cylinder pressure is a primary determinant of ionization potential at the moment of spark firing. Spark timing also affects average cylinder temperatures and therefore affects plug temperatures as well. There are no reliable rules of thumb governing ignition system requirements; they must be established on an engine dynamometer at the same time as other engine system parameters because all of these factors are interdependent.

Valve Timing and Intake Manifolds

Studies to date suggest that valve timing is not significantly affected by the fuel itself. Unique propane valve timing may be worthwhile, however, in order to take advantage of other propane engine differences such as compression ratio, emissions characteristics, and manifolding. Gasoline intake manifolds are intentionally designed to provide heating and also have flow restrictions to maintain high gas velocities. Propane power output is improved by thermal isolation and would also likely benefit from a manifold with flow characteristics designed specifically for gaseous fuels. As in the case of the carburetor, manifold design changes may also contribute to improved cylinder-to-cylinder distribution with resultant fuel economy gains.

Engine Durability

Valve seat wear is the principal durability problem encountered in a propane engine. The rate of exhaust valve seat wear usually increases by a factor of 5 to 10 when propane is used in an engine designed for unleaded gasoline. The use of high-alloy valve seat inserts will reduce wear, but it will probably remain higher than in a comparable gasoline engine. Additional changes, such as even better seat materials, or additives in the fuel or oil may be required if propane engines are to have valve and valve seat life equal to a gasoline engine. There is a critical need for a major effort to find ways of reducing valve seat wear; the number of propane vehicles which ultimately come into use will be heavily influenced by the extent to which this costly problem is solved.

Engine Lubrication

Despite a popular belief based on slower discoloration, there is no reason to believe that engine oil change intervals should be extended for propane-fueled engines. Limited testing has shown that some engine oil properties deteriorate at approximately the same rate with either fuel. Also, more testing is required to confirm that conventional SF oils are adequate for use in a propane engine.

Fuel Storage and Handling Systems

Propane tanks in shapes other than cylinders are needed to improve space utilization, particularly in passenger cars and small trucks. A tank material other than steel might be justifiable if it made a shape change possible or if it dramatically improved corrosion resistance, but it is very unlikely that it could be justified by weight reduction alone. A modest expenditure on further exploration of alternative shapes and materials appears to be worthwhile to clarify this significant yet poorly defined area.

There is a need for additional development regarding fuel tank corrosion protection. Minimum standards, particularly for aftermarket tanks, should be established. The relation between corrosion protection level and the need for, and frequency of, periodic inspection and recertification of tanks should be thoroughly explored. Ideally, a design level should be established which makes recertification unnecessary.

Fuel handling hardware and practices deserve high priority treatment. Compact, reliable, 80% stop fill valves that do not require emission of propane are being developed, but at a pace which suggests that additional R&D expenditure may be helpful. Safe, convenient, "self-serve" hardware with a standardized interface must be developed if propane is to reach full utilization as a motor fuel. Government participation in this area would be of particular value.

Certain existing fuel handling requirements deserve critical study to either reaffirm their need or recommend their abandonment. In some areas, rules such as "vehicle must be unoccupied when refueling" reinforce the public's fear of propane, and do not appear to be justified. A preliminary study of the need to purge new tanks of air indicates that this requirement also puts propane at a needless disadvantage with respect to gasoline.

Dual-Fuel Systems

Since it is expensive to produce a vehicle optimized for both propane and gasoline fuels simultaneously, dual-fuel systems will tend to involve some type of compromise. However, dual-fuel systems may be helpful in providing an introduction to propane for buyers who would not otherwise consider a propane-powered vehicle. It should be possible to develop a system which would have virtually optimum performance on propane and still provide an emergency gasoline system of limited range and performance. It is also possible to develop a system that offers acceptable operation on both fuels at a modest initial cost penalty. The feasibility of such a dual-fuel vehicle would of course be contingent upon adjusted or reinterpreted emissions standards for its operation on gasoline. It is important to recognize that, at present, most dual-fuel vehicles are converted without regard to federal gasoline emissions standards.

Low Temperature Operation

The best available aftermarket propane systems usually demonstrate deficiencies at ambient temperatures below -15°C. Many even exhibit problems at 0°C. When an engine block heater is used, the practical limit of operation for the best present systems extends to -40°C. This is the lowest temperature at which there is sufficient tank pressure to ensure adequate fuel delivery to the vaporizer

without using fuel blended to improve tank pressure. When a block heater is not used, other factors (cranking speed, battery voltage, etc.) quite apart from any fuel system limitations, preclude reliable starting of gasoline or propane engines when block temperatures drop below approximately -25°C. This is roughly equivalent to an overnight low of -30°C assuming normal overnight temperature change gradients. A major development effort is required to increase our understanding of the operation of propane at low temperatures and to improve the cold weather performance of propane fuel systems. There is no reason to expect propane to have cold weather performance inferior to gasoline; in fact, superior driveability, efficiency, and emission levels can be expected with propane during warmup at low ambients.

Propane Fuel Blends

It is sometimes suggested that the specification for automotive-grade propane should be revised to allow additional amounts of other fuel constituents. In considering this, we must pay close attention to seasonal vapour pressure, and to fuel mixture and octane rating requirements. Higher summer butane contents are possible and more ethane during the winter would improve fuel tank pressure. Propylene content should be limited to no more than 5% to avoid eroding octane ratings. The major drawbacks of allowing seasonal blending would be the effects it would have on engine design parameters, particularly fuel mixture requirements. There is a need for additional R&D in this area to quantify the benefits of fuel blends and to determine the effect of these changes on other engine parameters.

Health and Safety Considerations

Concerns regarding the relative safety of propane versus gasoline stem largely from unfamiliarity. Propane is not toxic; it is a simple asphyxiant that acts by diluting or displacing the oxygen content in the air. Natural gas and propane have odorants added so that their presence is easily detected. Long before propane becomes dangerous as an asphyxiant, its presence is very noticeable and offensive. Testing done by the federal governments in Canada and in Europe have shown that well-designed propane vehicles are safer than gasoline-powered vehicles in crash situations. Even when a propane tank was mounted on an immovable barrier and then impacted with a wedge-shaped piece of steel, no tank failure occurred despite severe damage.

STUDY RECOMMENDATIONS

The study concludes by recommending an R&D program to optimize propane engine and fuel system components. The program is broken down into major development groups (e.g. compression ratio, carburetion, fuel blends, etc.). Each group is further divided into smaller testing categories, many of which could be done separately. Each category includes a statement of the work objective, and an outline of the development testing procedure.

RÉSUMÉ

Le propane est un carburant sous-utilisé qui pourrait avantageusement remplacer l'essence, à condition toutefois que les économies soient intéressantes. La présente étude a été menée pour faire le point sur la technologie de la carburation au propane, repérer les perfectionnements possibles et définir un programme de recherche et de développement visant à optimiser les moteurs au propane et leur système d'alimentation.

Les conversions au propane comportent actuellement de nombreuses lacunes, la qualité technique des rééquipements étant liée à la fois à celle des composants utilisés et à des facteurs économiques. Dans les moteurs à essence convertis, l'usure rapide des sièges de soupape entraîne une défaillance prématurée des culasses. Ce problème ajouté aux autres fait que la qualité et le rendement des véhicules adaptés au propane varient énormément d'un cas à l'autre.

L'essence et le moteur à allumage actuel ont évolué en parallèle et il est carrément impossible de les dissocier l'un de l'autre, leurs propriétés étant inextricablement reliées. On ne peut donc changer de carburant sans modifier ou redessiner le moteur si l'on veut obtenir des résultats au moins comparables à ceux que donnait le carburant d'origine. D'ailleurs l'utilisateur voudra inévitablement comparer son véhicule équipé au propane aux véhicules à essence de même catégorie et, en plus d'une économie appréciable sur le carburant, il attendra de son véhicule une durée, des performances, une souplesse de conduite et une commodité comparables. Or, ce n'est que par la recherche et le développement au niveau des fabricants des matériels d'origine qu'on pourra atteindre ces objectifs. Voici donc quelques points à considérer.

Taux de compression

La consommation et la puissance des moteurs au propane peuvent être améliorées de façon appréciable en augmentant les taux de compression. Cependant, l'augmentation de ce taux et les avantages correspondants sont limités par certaines contraintes de fabrication et de fiabilité des organes du moteur et aussi par les risques de cognement ou de détonation au-delà d'un certain seuil (voir le paragraphe consacré à l'allumage). Le propane et l'essence n'ayant pas les mêmes propriétés détonantes, on ne peut donc se baser sur les acquis concernant l'indice d'octane de l'essence pour prévoir la résistance du propane à la détonation, à des taux de compression qui, de toute façon, sont plus élevés. Seules des recherches spécifiques à chaque type de moteur permettront de mieux définir la relation entre ces deux facteurs et de déterminer le taux de compression maximal utilisable.

Carburation

Le moteur au propane tolère de plus grands écarts par rapport au mélange carburé idéal que le moteur à essence, sans éprouver de sérieux problèmes au niveau de la souplesse de marche. C'est ce qui explique que des carburateurs à gaz relativement simples aient pu être utilisés et donner satisfaction, à en juger par la réaction générale des utilisateurs. Pourtant, ces carburateurs sont loin d'autoriser une consommation, une puissance et une souplesse de marche optimales. Or, une carburation améliorée permettant, par exemple, d'enrichir le mélange à l'accélération, de l'appauvrir en régime normal et même de couper l'alimentation lors des décélérations, contribuerait certainement à faire avancer les moteurs au propane sous ces rapports. Contrairement à la croyance générale, une alimentation en phase gazeuse n'assure pas nécessairement une bonne répartition du mélange entre les cylindres. En fait, des essais ont montré que la répartition n'est probablement pas meilleure qu'avec l'essence, excepté durant le réchauffement et aux faibles vitesses d'écoulement dans les tubulures d'admission. Un carburateur qui donnerait un mélange plus homogène permettrait sans nul doute de réduire la consommation, car un mélange généralement plus pauvre pourrait être utilisé. Mais le perfectionnement des carburateurs et l'évaluation chiffrée des gains qu'ils pourraient apporter nécessitent des investissements considérables sans lesquels il y a peu de chance que la technologie des carburateurs évolue à un rythme qui jouera en faveur de l'option propane.

Allumage

Les caractéristiques de combustion du propane et de l'essence présentent des différences appréciables sur les plans du retard à l'allumage et de la vitesse de propagation de la flamme à l'intérieur du cylindre. Comme l'avance à l'allumage est principalement fonction de ces deux facteurs, le calage du point d'allumage ne sera pas le même non plus. Les propriétés antidétonantes du propane soulèvent un problème particulier étant donné que le cognement ne survient pas aux mêmes régimes moteur qu'avec l'essence. En effet, dans un moteur à essence, la détonation se produit normalement à bas régime; le cliquetis étant alors clairement audible, il est possible de faire les réglages voulus avant que le moteur ne soit endommagé. Par contre, dans un moteur au propane, ce phénomène se produit plutôt aux régimes élevés et le cliquetis, masqué par les autres bruits du moteur, risque de passer inaperçu et de causer de sérieux dommages. La pratique courante qui consiste, dans les ateliers de rééquipement, à avancer l'allumage à bas régime et à le retarder à régime élevé peut avoir pour résultat de réduire inutilement la puissance du moteur, dans certains cas, sans éviter le cliquetis dans d'autres. Il est donc nécessaire d'optimiser expérimentalement le calage du point

d'allumage et d'empêcher la détonation avec le carburant ayant le plus faible indice d'octane.

D'autres idées fortement répandues concernant la tension, l'énergie d'allumage et la température des bougies, semblent mal fondées. Ainsi, on ne peut relier la tension d'allumage uniquement au calage du point d'allumage, car la pression à l'intérieur du cylindre intervient pour beaucoup dans le potentiel d'ionisation au moment de l'éclatement de l'étincelle. Le calage de l'allumage influe également sur la température moyenne à l'intérieur du cylindre et, par conséquent, sur la température de la bougie. Il n'existe aucune règle empirique fiable concernant les exigences applicables au système d'allumage; celles-ci doivent être établies sur banc d'essais, en même temps que tous les autres paramètres de fonctionnement du moteur, étant donné que tous ces facteurs sont interdépendants.

Distribution et collecteur d'admission

Les études menées à ce jour laissent penser que le carburant lui-même n'influe pas de manière appréciable sur le réglage de la distribution, mais il peut être intéressant de régler la distribution spécifiquement pour le propane, mettant ainsi à profit les autres particularités du moteur au propane, comme le taux de compression plus élevé, le niveau réduit des émissions polluantes et le collecteur d'admission. La conception des collecteurs d'admission des moteurs à essence vise en premier lieu le réchauffement du mélange carburé et prévoit aussi des étranglements servant à maintenir une vitesse d'écoulement élevee de celui-ci. La puissance d'un moteur au propane dépend d'une bonne isolation thermique du collecteur; elle peut être augmentée par un collecteur possédant des caractéristiques d'écoulement conçues pour un carburant gazeux. Au même titre que les perfectionnements du carburateur, la réétude du collecteur d'admission pourrait contribuer elle aussi à améliorer la répartition du mélange entre les cylindres et à réduire la consommation.

Durée du moteur

La durée utile des moteurs au propane est affectée principalement par l'usure des sièges de soupape. Dans un moteur conçu pour une essence sans plomb, mais alimenté au propane, ces sièges s'usent de 5 à 10 fois plus vite. L'emploi de sièges de soupape rapportés à haute teneur en alliage peut certainement ralentir l'usure, mais jamais assez pour atteindre le rythme d'usure caractéristique des moteurs à essence comparables. Pour donner aux soupapes et aux sièges une durée égale à celle qu'ils auraient dans un moteur à essence, il faudrait d'autres changements comme l'utilisation de matériaux plus résistants encore, ou l'emploi d'additifs dans le carburant ou les lubrifiants.

En fait, il faut de toute urgence consentir tous les efforts nécessaires pour éliminer ce problème car, tout compte fait, la généralisation de la propulsion au propane dépendra largement de la solution qui aura été trouvée.

Lubrification

Contrairement à la croyance générale, fondée sur une décoloration moins rapide de l'huile dans les moteurs au propane, rien n'indique qu'on doive espacer les vidanges d'huile dans leur cas. Des essais limités ont montré que certaines propriétés des huiles à moteur se dégradent aussi rapidement dans un cas comme dans l'autre. Par ailleurs, il faudra mener des essais plus poussés pour déterminer si les huiles SF conviennent aux moteurs alimentés au propane.

Stockage et manutention du carburant

Il faudrait pouvoir remplacer la traditionnelle bouteille de gaz par un réservoir dont la forme permettrait une meilleure utilisation de l'espace, particulièrement dans les véhicules de tourisme et les petits camions. Quant au remplacement de l'acier comme matériau de fabrication, il se justifierait par la possibilité d'obtenir des réservoirs de forme différente ou par une résistance à la corrosion radicalement améliorée, mais il est très peu probable que la réduction de poids autorisée suffise à elle seule à justifier le changement. Il semble qu'il vaudrait la peine de consentir une injection modeste de fonds nouveaux pour la recherche de formes et de matériaux différents, si ce n'est que pour mieux cerner cette importante question encore très mal définie.

La protection anti-corrosion doit faire l'objet d'une étude de mise au point plus poussée. Des normes minimales doivent être établies, plus particulièrement pour les réservoirs de rééquipement. Il faudrait également étudier à fond la question des programmes d'inspection et de "rehomologation" périodiques à instaurer selon le degré de protection anti-corrosion réalisé. Idéalement, il faudrait parvenir à une qualité de construction telle que le problème de la "rehomologation" ne se pose même plus.

Le matériel et les méthodes de manutention du carburant méritent une attention toute particulière. Actuellement, on met au point des robinets de remplissage automatique fiables et de faible encombrement qui ne produisent aucun rejet de propane dans l'atmosphère. Cependant, les travaux n'avancent pas très rapidement et il serait utile d'injecter des fonds R&D additionnels. Il importe de mettre au point un matériel sûr, pratique et normalisé, utilisable par tous, si l'on veut réaliser pleinement le potentiel d'utilisation du propane. Signalons que la participation gouvernementale serait ici un atout particulier.

Certaines exigences concernant le remplissage des réservoirs de propane doivent être remises en question afin de décider si on doit les abandonner ou les confirmer. Dans certaines régions, la réglementation stipule que les véhicules au propane doivent être inoccupés pendant le remplissage du réservoir et ne fait que renforcer les craintes du public vis-à-vis de ce carburant, sans être pour autant nécessairement justifiée. Par ailleurs, une étude sommaire a montré que l'obligation de purger l'air des réservoirs neufs place le propane en désavantage injustifié par rapport à l'essence.

Systèmes bi-carburant

Comme le coût d'un véhicule offrant un rendement optimal à la fois à l'essence et au propane risque d'être très élevé, les systèmes bi-carburant constitueront inévitablement une sorte de compromis. Malgré tout, ces systèmes pourraient contribuer à attirer des utilisateurs qui autrement n'auraient pas été intéressés par un véhicule au propane. Il devrait être possible de mettre au point un système qui présenterait un rendement pratiquement optimal au propane, et qui pourrait, en cas de nécessité, fonctionner à l'essence mais avec un rendement et un rayon d'action réduits. Il est également possible de mettre au point un système offrant un fonctionnement acceptable avec les deux types de carburants, moyennant un coût initial légèrement plus élevé. La réalisation d'un tel véhicule bi-carburant serait évidemment conditionnelle à l'adoucissement des normes concernant le niveau de ses émissions polluantes lorsqu'il fonctionne à l'essence. Il faut bien reconnaître qu'à l'heure actuelle la plupart des conversions bi-carburant sont réalisées sans tenir compte des normes antipollution frappant les moteurs à essence.

Fonctionnement par temps froid

Les meilleurs systèmes au propane offerts en rééquipement présentent certaines lacunes lorsque la température ambiante descend sous -15°C; d'autres fonctionnent mal dès que la température atteint 0°C. Un chauffe-bloc permet de repousser la limite de bon fonctionnement à -40°C dans le cas des systèmes les mieux conçus, mais au-delà de cette température, il ne subsiste plus dans le resérvoir une pression suffisante pour assurer une alimentation correcte du vaporisateur, à moins qu'on utilise un mélange spécialement préparé. Sans chauffe-bloc, les problèmes de démarrage à froid commencent à apparaître lorsque la température du bloc-moteur atteint -25°C environ et ce sont d'autres facteurs (régime de lancement trop faible, tension réduite de la batterie, etc.), qui n'ont rien à voir avec le type de carburant utilisé, qui sont à l'origine des problèmes. Pour avoir cette température au bloc-moteur, il faut que le minimum ait été de -30°C la nuit et que les gradients de variation aient suivi la courbe normale. Des moyens importants devront être mis en oeuvre pour approfondir notre

connaissance du comportement du propane aux basses températures et pour améliorer le rendement des moteurs au propane par temps froid. A priori, le propane ne devrait pas donner un rendement inférieur à l'essence, dans ces conditions; en fait, il devrait lui être supérieur sur le plan du rendement, de la souplesse de marche et du niveau des émissions polluantes, au moins durant la période de réchauffage.

Composition du carburant au propane

Il a été proposé, à quelques reprises, de réviser les spécifications concernant le carburant au propane afin de relever la proportion de ses autres éléments constitutifs. Toute modification de ce genre doit prendre en compte les variations saisonnières de la tension de vapeur ainsi que les caractéristiques de combustion et l'indice d'octane souhaitables selon la saison. On pourrait, par exemple, relever la teneur en butane l'été tandis qu'une proportion plus grande de méthane en hiver permettrait de maintenir une pression plus grande dans le réservoir par grand froid. Il faudrait cependant limiter la teneur en propylène à 5% afin de ne pas réduire l'indice d'octane. L'utilisation de mélanges saisonniers présente certains inconvénients dont le principal est l'incidence sur les paramètres moteur, et plus particulièrement sur la carburation. Il serait nécessaire de pousser davantage la recherche et le développement dans ce domaine afin de pouvoir quantifier les avantages procurés par les différents mélanges et déterminer les effets de ces changements sur les autres paramètres moteur.

Sécurité

Le propane n'est pas plus dangereux que l'essence et s'il suscite des craintes, c'est surtout que son utilisation comme carburant automobile est encore mal connue. Il n'est pas toxique et n'entraîne l'asphyxie qu'à forte concentration. Le gaz naturel et le propane, naturellement inodores, ne le sont plus après traitement industriel de sorte que les fuites ne peuvent plus passer inaperçues. En fait, les fuites de propane se remarquent bien avant qu'il y ait risque d'asphyxie, grâce à une odeur artificielle volontairement très désagréable. Les essais menés par les autorités canadiennes et européennes de la sécurité routière ont montré qu'un véhicule au propane bien conçu présente moins de risques en cas de collision que les véhicules à essence. Aux essais de choc par mouton-pendule en forme de coin, aucun des réservoirs testés n'a laissé échapper son contenu bien qu'ils aient tous été gravement déformés.

RECOMMANDATIONS

Les promoteurs recommandent de lancer un programme R&D visant à optimiser les moteurs au propane et les systèmes d'alimentation correspondants. Ils proposent un programme détaillé qui définit les grands thèmes de la recherche préconisée (taux de compression, carburation, composition des carburants, etc.) et présentent un plan de réalisation structuré de telle manière que les divers éléments puissent être entrepris séparément s'il le faut. Pour chacun des éléments du Programme, ils proposent de poursuivre l'objectif, en plus d'esquisser le mode opératoire des essais envisagés.

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1. INTRODUCTION

1.1 Purpose of the Study

The principal purposes of this study are:

- to review the current state of the art relating to propane-fueled light duty vehicles including the problems and deficiencies of currently available vehicles;

- to identify the opportunities for optimizing the overall performance and consumer acceptance of propane-fueled light duty vehicles;

- to define a research and development program aimed at optimizing several popular light duty vehicle/engine combinations using propane as a fuel.

1.2 Background

The upheaval in the worldwide marketing of oil from 1973 to 1982, which saw the price of oil rise from $3 per barrel to $38 per barrel, forcibly brought home to the western nations the vulnerability of their oil supplies and its significance to their economies. In response to this threat, the government of Canada established a National Energy Program directed at achieving energy independence for Canada. A fundamental part of that program is to make Canada self-sufficient in oil by 1990. This goal is to be achieved by a combination of programs to increase production and reduce demand. An important element of the program to reduce the demand of petroleum-based fuel is to promote the use of alternative fuels such as natural gas and propane to replace gasoline and diesel fuel.

Propane has been used for many years as an internal combustion engine fuel, particularly for large stationary power plants and for trucks. Because of its good supply situation and a rapidly growing distribution network, propane is a prime candidate as an alternative to gasoline in spark ignition engines for passenger cars and trucks.

When crude oil was $3 per barrel, there was little incentive for the motor vehicle manufacturers to explore alternative fuels and, as a result, engines and fuel systems have been developed and optimized almost exclusively for gasoline. The conversion of vehicles and engines from gasoline to propane has been largely left to propane equipment manufacturers and aftermarket conversion specialists. These conversions usually involve compromises particularly when the vehicle is equipped with a dual-fuel system intended to run on either gasoline or propane. Even with a single-fuel propane conversion, there is a limit to the degree of optimization that is technically or

economically feasible in the aftermarket. Dramatically higher prices and potential shortages of oil have therefore set the stage for the design and production of passenger cars and trucks that are optimized for propane.

1.3 Phase I of Program

The contract for this study resulted from an unsolicited proposal by Chrysler Canada Ltd. to the Science Procurement Centre of the Department of Supply and Services. The Product and Development Engineering Department of Chrysler Canada Ltd. agreed to carry out the project under the overall direction of Transport Canada's Transportation Development Centre beginning May 1, 1982.

This contract is phase I of a four phase program intended to bring to the marketplace light duty vehicles optimized for the use of propane. The four phases of the total program are:

Phase I - Program definition of an R&D program to optimize vehicles and engines for propane.

Phase II - Research and development and prototype design of an optimized propane vehicle.

Phase III - Design verification and tooling.

Phase IV - Production implementation

2. PROPANE AS AN AUTOMOTIVE FUEL

2.1 Background and History

Although we speak of propane as an alternative fuel to gasoline, the use of gaseous fuels in spark ignition engines is not new. Some of the earliest forms of internal combustion (I.C.) engines used coal gas until liquid petroleum fuel, with its simpler storage requirements and its superior heating value on a volume basis, won out. Nevertheless, propane and liquified petroleum gas (LPG) have been used for decades whenever a cheap, reliable supply was available, especially for farm tractors and stationary engines in the oil and gas fields. The low level of carbon monoxide emissions also made LPG desirable as a fuel for engines used in mines and for fork lift trucks in factories. Utility companies producing and distributing propane/LPG also found it to be an economical fuel for their trucking operations. Other commercial truck fleets followed suit with variable results, depending on the quality of the conversion of the vehicle used.

In the 1950's, many propane users experienced severe engine detonation which was traced in part to excessive amounts of propylene in refinery-produced LPG. Propane and butane, the major constituents of LPG, have excellent anti-knock properties. But propylene has a much lower octane rating. As a result, the Gas Producers Assoc., and subsequently the American Society for Testing Materials (ASTM) developed an automotive quality specification for propane, HD-5; ASTM D1835; it is covered in Canada by CGSB Specification Can 2-3.14-M78 Grade 1. This gave the automotive industry a standardized high quality LPG fuel with a minimum propane content of 90% and assured a motor octane rating of 95.

While the price of gasoline remained low in North America, the demand for propane was confined largely to commercial fleets and farm tractors. There was a passing flurry of interest by environmental regulating agencies in the United States, particularly in California, during the early 1970's because of propane's very low carbon monoxide and hydrocarbon exhaust emissions compared to gasoline. It was the recurring energy crisis in the 1970's and the formation of the Organization for Petroleum Exporting Countries (OPEC) which brought renewed interest in propane as an automotive fuel. The ever-increasing price of gasoline and the recognition of our dependency on imported oil have sparked great interest in Canada by governments, the motoring public, and by the oil and gas producers and distributors.

These same events have had their impact in Europe, where retail fuel prices have traditionally been much

higher than those experienced in Canada. In some countries, particularly Italy and Holland, propane and butane have replaced gasoline on a significant scale. In 1981, LPG automotive fuel sold in the Netherlands amounted to 16.5% of the gasoline sold, and in Italy sales were 6.3% of gasoline (Ref. 1).

The spark ignition engine has been developed hand in hand with the development of gasoline; they have evolved together with the closest cooperation between the automotive and oil industries, especially under the auspices of the Coordinating Research Council, a joint body representing both industries. All alternative engines and fuels will, therefore, be evaluated and compared, consciously or otherwise, with the gasoline spark ignition engine; it is the standard.

If any alternative fuel is to receive wide acceptance, it must meet certain requirements or have acceptable trade-offs:

- perform in the vehicle as well as gasoline from a starting, performance, and driveability standpoint.
- have long-term economic advantage over gasoline as measured in cost per kilometre.
- be readily and widely available to permit unrestricted travel.

It is unlikely that each of these requirements will be completely fulfilled in the beginning any more than gasoline satisfied each in the early days of motoring. On the other hand, it will be absolutely essential for the alternative fuel to have economic advantage and secondly it must perform without any serious shortcomings. As those two requirements are met, distribution will not be far behind.

2.2 Properties of Propane

Propane is a component of LPG, a term covering a mixture of petroleum hydrocarbons consisting mainly of propane and butane, but it may also contain quantities of ethane, propylene, and butylene. These hydrocarbons are all gaseous at atmospheric temperature and pressure but when stored in a pressure vessel remain liquid under the influence of their own vapour pressure at normal ambient temperatures.

Automotive quality propane containing a minimum of 90% propane provides the North American motorist with a high quality fuel. Nevertheless, in many parts of the United States "commercial" propane with varying amounts of other LPG components is still regularly used but not always with satisfactory results.

In Europe there is no automotive standard and the composition of LPG varies from country to country as a result of supply and climate variations. In Italy, LPG is predominantly butane, while in northern Europe, the colder climate requires a fuel with a higher vapour pressure and is, therefore, predominantly propane. See Table 1.

COUNTRY	PERCENT C_3* IN LPG
WEST GERMANY, SWEDEN, U.K.	85-95
NETHERLANDS, BELGIUM	40-55
FRANCE	19-50
*ITALY	20

* C_3= Propane and propylene

TABLE 1 Percent C_3 in LPG Sold as Automotive Fuel in Europe

An understanding of the basic properties of propane and how they differ from the properties of other hydrocarbon fuels, particularly gasoline, is necessary if propane is to be used to the best advantage. Table 2 compares the more important qualities of propane and the associated compounds found in LPG together with CGSB Grade 1 propane and gasoline. The properties of these hydrocarbons are all related to their performance as an automotive fuel.

- Boiling point and vapour pressure are directly related. They are important to propane-fueled vehicles because no fuel pump is used and the vapour pressure in the tank forces the liquid fuel to the vaporizer. As the ambient temperature drops to a point where the vapour pressure equals the atmospheric pressure (-42°C for pure propane), delivery of the fuel can become a problem.

- Heat of vaporization is the amount of heat required to vaporize the propane. This is supplied by engine coolant flowing through the vaporizer and, therefore, cold starts and operation before the engine is warmed up are matters to be considered.

- The density of liquid propane is less than gasoline and therefore a given volume of propane weighs 70% of the same volume of gasoline. This means that although propane has a higher heating value per unit weight, it provides less heat per unit of volume.

- Density of propane gas is heavier than air and any leakage tends to hug the ground rather than rising and dispersing more readily in the air. This becomes a factor in designing ventilation systems of service

	PROPANE	PROPYLENE	N. BUTANE	ISO BUTANE	ETHANE	PROPANE* GRADE 1	GASOLINE
CHEMICAL FORMULA	C_3H_8	C_3H_6	C_4H_{10}	C_4H_{10}	C_2H_6	97.5% C_3	C_4-C_{14}
BOILING POINT AT 1ATM.-°C	-42.1	-47.7	-0.5	-11.7	-88.9	-42	27-230
VAPOUR PRESS. AT 25°C - kPa	936	1147	244	347	4114	930	---
38°C - kPa	1310	1567	356	498	---	1435 max	62-97
HEAT OF VAP. - kJ/kg	428	438	386	366	488	427	300 at mid B.P.
SPECIFIC GRAVITY AT 15.5°C	.508	.522	.584	.563	.377	.510	.730
REL. DENSITY OF GAS AT 15.5°C (AIR=1)	1.56	1.45	2.07	2.07	1.04	1.57	---
STOICH. FUEL/AIR RATIO	.0638	.0676	.0647	.0647	.0621	.0640	.0685
STOICH. AIR/FUEL RATIO	15.7	14.8	15.5	15.5	16.1	15.6	14.6
NET HEAT OF COMB MJ/kg	46.3	45.8	45.7	45.6	47.5	46.2	43.3
MJ/L	23.5	23.9	26.7	25.7	17.5	23.6	31.6
MOTOR OCTANE NO.	97	85	89	98	99	95	82-92
RESEARCH OCTANE NO.	112	102	94	100	115	108	91-100

* -CGSB Spec -Can 2 - 3.14 - M78 - equivalent to HD.5
Assumes 92.5% propane; 2.5% butane; 5% propylene

TABLE 2 Properties of Propane, Gasoline and other LPG Compounds

garages and indoor parking areas.

- Stoichiometric or chemically correct fuel-air ratio for perfect combustion is less for propane than for gasoline.

- Heat of combustion - compared to gasoline, Grade 1 propane provides 7% more heat on a weight basis and 25% less heat on a volume basis.

- Motor and Research octane are measures of the anti-knock property of a fuel under specific test conditions. Motor octane is measured at 900 rpm with an inlet air temperature of 300 F, while Research octane is measured at 600 rpm and 125 F. Spark timing conditions for the two tests are also different. With gasoline, most engines react approximately equally to changes in Research and Motor values. With propane, the Motor octane value is much more important. The higher octane rating for propane permits higher compression ratios and therefore increased efficiency. This can help to compensate for the lower heating value of propane per unit volume.

2.3 Combustion Characteristics of Propane

Despite the fact that propane is one of the most widely used alternatives to gasoline in spark ignition (S.I.) engines, there is very little fundamental information available on its combustion characteristics in an S.I. engine. Nevertheless, a very informative report was made by Andoh et al (Ref. 2) on their investigations comparing propane and other alternative fuels with gasoline. Using a single cylinder engine, their work mainly measured heat release characteristics of the fuels tested while varying spark timing, air-fuel ratios and compression ratios.

Figure 1 shows the rate of heat release (RHR) and also the accumulated heat release at spark timing = 25° before top dead centre (BTDC), compression ratio (CR) = 8.5, and air-fuel equivalence ratio (Fr) = 1*. An examination of Figure 1 shows that there is a lag following the spark at the plug, point It, before there is any perceptible heat release. This duration is termed ignition delay = Tf. The duration from It to the point of 10 percent accumulated heat release is termed Heat Release Delay (Thr). The next significant point is where the rate of heat release reaches a maximum = T(dq/dθ)max and finally the time to 90% accumulated heat release = Tm, where combustion is deemed to be complete for all practical purposes.

* Fr = Fa/Fc, where Fa is the actual fuel-air ratio and Fc is the chemically correct fuel-air ratio.

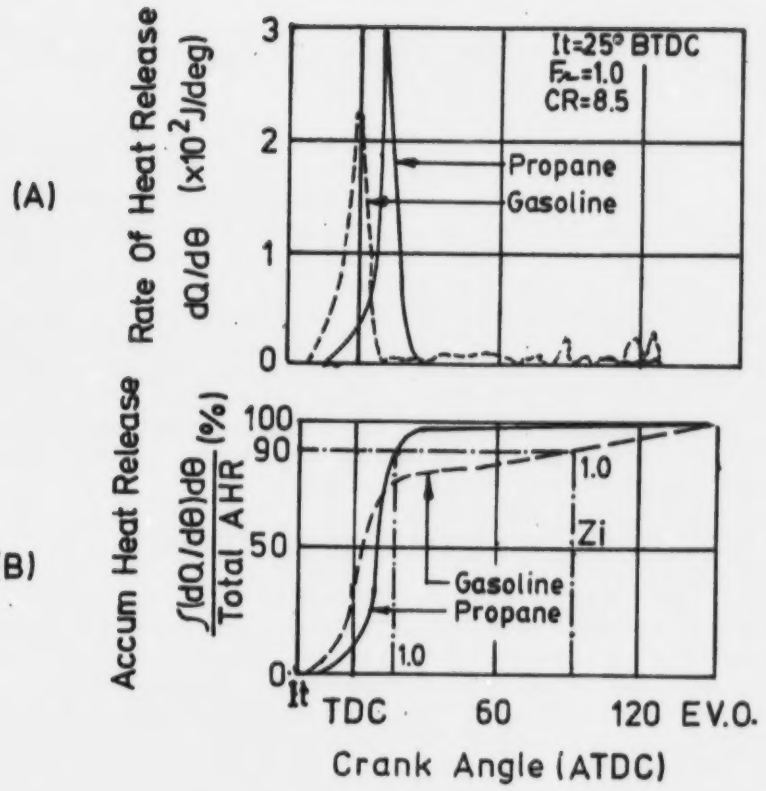


Figure 1 Typical Diagrams of Rate of Heat Release and Accumulated Heat Release
(A) Rate of Heat Release
(B) Accumulated Heat Release
(Ref. 2)

This study also uses a further convention for analysis. The accumulated heat release (AHR) at any point is divided by the 90% heat release value to give a dimensionless number, Zi. This is plotted against another dimensionless number, Xi, defined as the time from It divided by the time to 90% heat release, Tm. Figure 2 shows this relationship for the values in Figure 1.

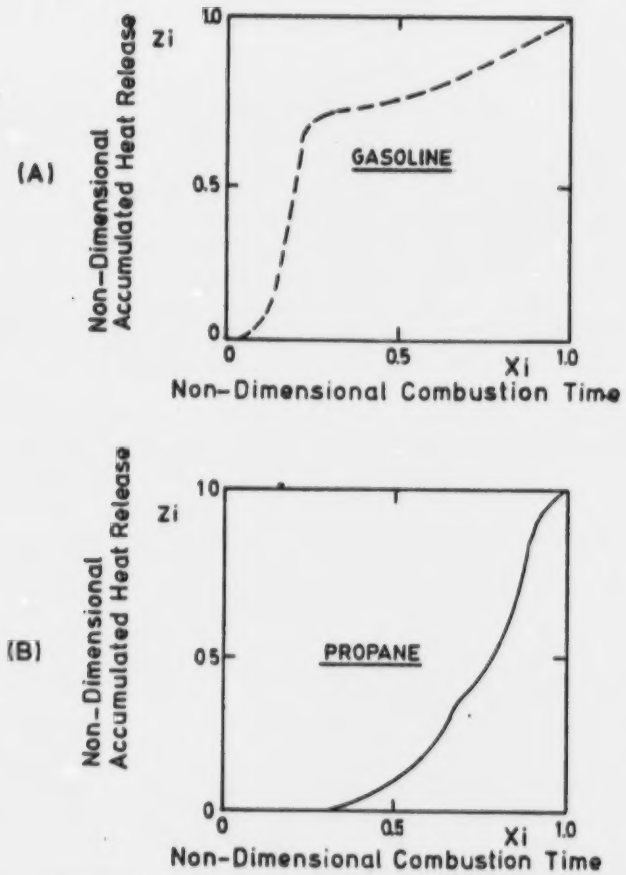


Figure 2 Typical Diagrams Of The Relation Between Non-Dimensional Accumulated Heat Release And Non-Dimensional Combustion Period For (A) Gasoline And (B) Propane.
Zi=1.0 Means The 90% Heat Release Point.
Xi=1.0 Means The Time At The 90% Heat Release Point.
(Ref. 2)

Certain observations can be made concerning the data presented here and in the referenced study:

- Propane has a longer ignition delay (Tf) than gasoline
- Propane has a much higher rate of heat release than gasoline
- At Fr = 1, although propane has a longer ignition delay, the high rate of heat release causes combustion to be complete (Tm point) much sooner than gasoline. For conditions in Figure 1, propane combustion is

complete at 20^{o} after top dead centre (ATDC) while gasoline is not complete until 90^{o} ATDC.

For the influence of air-fuel ratios and compression ratio changes on combustion characteristics of propane and gasoline, the original paper should be consulted. Only sufficient data has been presented here to point out that the combustion characteristics of the two fuels in an S.I. engine are substantially different. It would be unwise to draw hard conclusions at this time since the work discussed was carried out with a single cylinder engine at one speed (600 RPM), an engine speed approximating the idle condition of an automotive engine. The influence of higher engine speeds needs to be determined.

Nevertheless, the study suggests that optimizing an engine for the use of propane may require a more complete understanding of the combustion characteristics of propane.

2.4 Conclusions and Recommendations

(1) Propane can be an excellent alternative to gasoline in a spark ignition engine.

(2) The incentive to use propane instead of gasoline is dependent upon:
- the overall economic benefits
- the development of engine-propane systems that perform as well as gasoline
- the widespread availability of propane

(3) Combustion characteristics of gasoline and propane are different and more basic research into the combustion characteristics of propane in a spark ignition engine may be helpful in providing information to optimize engine systems using that fuel.

(4) CGSB Grade 1 propane specification ensures a high quality automotive fuel. This standard should be maintained but there is a case for considering seasonal blends permitting a higher butane content in the summer months. This subject is discussed in section 8.

(5) High octane values for propane generally permit higher compression ratios than are possible with gasoline providing an opportunity for improved power output and fuel economy.

3. VEHICLE PROPANE SYSTEMS TODAY

3.1 Overview

Propane conversion hardware has been developed by a large number of small manufacturers, many of which manufacture and assemble conversion kits for the aftermarket. These manufacturers are predominantly located in Europe, particularly the Netherlands and Italy, in the U.S.A. and Japan. Although industrial engine manufacturers such as Waukesha, Kohler and Chrysler have for decades marketed natural gas and propane engines as an original equipment manufacturer (OEM) option, the installation of propane equipment on cars and trucks in North America has been very much an aftermarket activity. Some manufacturers have offered a limited range of propane-powered trucks but, for the most part, conversion of cars and trucks from gasoline to propane has been carried out by fleet owners themselves or by conversion centres.

In Europe, a similar situation exists, but since most trucks are diesel powered, the switch from gasoline to propane is in the passenger car sector. The two countries in Europe with the largest fleets of propane cars are Italy with 730 000 and the Netherlands with 370 000 (1980 data Ref. 3), which make up a substantial portion of the total car fleets in these two countries. Despite this volume, European conversions are exclusively carried out in the aftermarket, primarily because of taxation policies. Except for France, conversions are all dual-fuel versions with propane equipment added to vehicles designed and built for gasoline. In France, dual-fuel vehicles are not permitted and the use of propane for automotive use is negligible.

In Japan, where the use of propane for Tokyo taxicabs is mandatory to reduce carbon monoxide emissions, the car manufacturers do market taxicabs for propane only.

Individual components and their application to different vehicles reveal a wide range of manufacturing quality and level of engineering development, both of which are reflected in a very wide range of performance in vehicles. As one group of researchers aptly put it, "the application of propane to motor vehicles is far ahead of its research" (Ref. 2). To be fair, there is a limit to the degree of optimization that can be economically or practically carried out in an aftermarket conversion and the limitation is even greater if the conversion is to a dual-fuel unit. Because propane is a "forgiving" automotive fuel, being completely volatile, having wider ignition limits than gasoline, and excellent octane ratings, less than adequate installations are often tolerated by the vehicle operator.

The stage seems to be set for a considerably deeper involvement on the part of vehicle manufacturers. This is not to suggest that they should take over the manufacture of propane system hardware, but that they will, in conjunction with propane component manufacturers, tailor the component specifications to their unique needs, optimize their engines and vehicles for propane, and develop the overall packaging of the system to ensure safety, reliability, performance and fuel economy.

3.2 Regulations

If research is having difficulty keeping pace with the application of propane to motor vehicles, so too are regulations governing the components and installation of propane equipment on vehicles barely keeping abreast of the developing technology and its application.

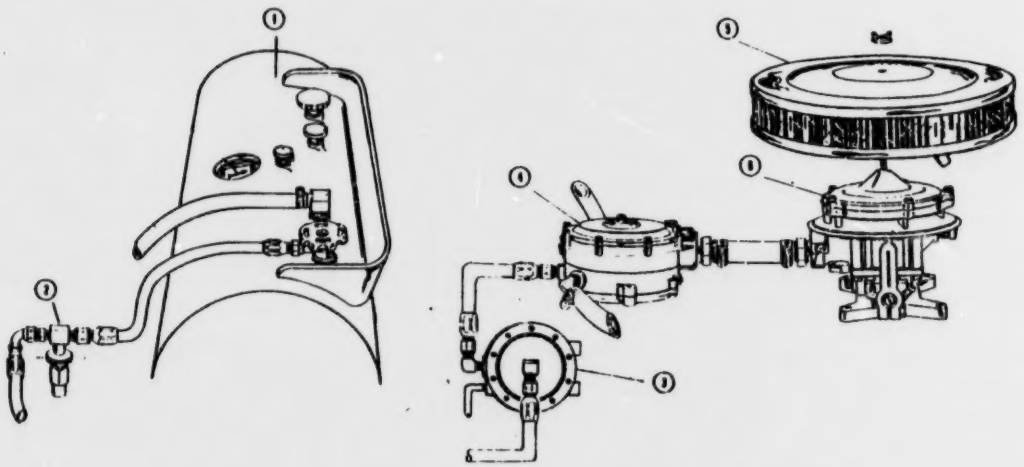
In Europe, there is considerable activity being directed at standardizing regulations and specifications under the auspices of the Economic Commission for Europe (ECE) in cooperation with other European and world organizations such as Bureau Permanent International des Constructeurs d'Automobiles (BPICA, worldwide motor vehicle manufacturers association). This activity is being followed closely by the Canadian and United States Motor Vehicle Manufacturers Associations to ensure that the North American industry remains abreast of developments in other parts of the world.

For propane vehicles sold in Canada, vehicle manufacturers are regulated by Canadian Federal Motor Vehicle Safety Standard (MVSS) 301.1, which gives the manufacturer an option of demonstrating the integrity of the fuel system by a barrier crash test or by complying with the Canadian Gas Association (CGA) Preliminary Standard 12.2 "Propane Fuel System Components for Highway Vehicles" and the applicable installation requirements of those components as specified in the National Standard of Canada, Can 1-B 149.2-M80 Installation Code for Propane Burning Appliances and Equipment dated December 1980, "except as modified by MVSS 301.1."

Aftermarket components and installation come under the jurisdiction of the individual provinces. The CGA Preliminary Standard 12.2 for components is intended as a guide for the provinces and eventually all provinces will probably require the component manufacturer to obtain type approval. The National Standard of Canada Can 1-B 149.2-M80 covering the installation of propane equipment is also intended as a guide for the provinces. Hopefully, the end result will be a common set of standards across Canada for the aftermarket.

3.3 Typical Systems

Although propane systems may vary in sophistication and refinement, they all operate on the same basic principles. The system consists of a storage tank containing liquid propane which is delivered to an integrated vaporizer/pressure regulator (commonly called a converter) by the vapour pressure of the propane in the tank (Figure 3).



1. Propane Fuel Tank
2. Hydrostatic Relief Valve
3. Vacuum Fuel Shut-off & Filter
4. Fuel Pressure Regulator & Vaporizer
5. Air Cleaner
6. Carburetor

Figure 3 Typical Propane System

The function of the vaporizer is to vaporize the propane into a completely dry gas and to reduce and stabilize the gas pressure available to the air-fuel mixing unit or carburetor. Vaporization of the liquid propane requires the addition of heat (218 kJ/L) and this is supplied in most cases by circulating engine coolant through the vaporizer. The propane gas is then drawn into the carburetor and mixed with the inducted air.

The fuel tanks and their auxiliary valves and hardware are very similar from one system to another. All must meet specific pressure vessel requirements and incorporate a filling connection, a pressure relief valve, a service

shut-off valve, a fuel contents gauge or sending unit, and a fixed liquid level gauge to indicate when the fuel tank has reached 80% capacity, the legislated maximum amount to which a tank may be filled.

Between the fuel tank and the vaporizer it is also necessary to incorporate a hydrostatic relief valve to protect the fuel lines from possible rupture, and a fuel shut-off valve which will allow fuel to flow to the vaporizer only when the engine is turning. A filter is also usually located in the liquid fuel line between the tank and the vaporizer.

The major differences between commercial systems result from the many designs and forms of the vaporizer and the air/fuel mixers. Almost all vaporizers provide exit gas at or slightly below zero gauge pressure with very few having outlet pressure above zero. All are similar in basic design using diaphragm and lever valves but they vary considerably in capacity and performance. Fuel/air mixers or carburetors come in a wide array of types and sizes most of which use a conventional butterfly valve to control the flow of air into the engine. All types use the inducted air to create a depression by which the propane gas is drawn into the carburetor to be mixed with the air.

Many carburetors use various styles and designs of venturis to meter fuel into the air stream. Air valve carburetors measure the flow of air and in turn lift a profiled gas valve off its seat to match the gas flow to the inducted air flow.

Since propane enters the intake system as a gas and there is no liquid fuel in the intake manifold, the fuel-air ratio metered by the carburetor is essentially the same as seen by the engine under all conditions including transient operation and so no accelerator pump is required as with a gasoline carburetor. With gasoline, a choke is required to provide a very rich liquid fuel-air ratio during cold engine operation to ensure that sufficient fuel vapour enters the cylinder. Since propane is already a gas, no choke or enrichment is necessary during engine warmup.

For aftermarket dual-fuel conversions, there is very little that can be done to modify the engine to optimize the performance in the propane mode because any change would detract from its performance when using gasoline, and probably invalidate the manufacturer's warranty. For single-fuel propane vehicles it is the usual practice to modify the engine to some degree.

- Intake manifold heat riser:
  Gasoline engines have an exhaust gas or hot water heated intake manifold to help vaporize the fuel. Propane, being a gas, does not need this heat and

indeed the addition of heat will expand the incoming charge and lower volumetric efficiency. High intake temperatures also increase the risk of ignition knock or detonation. The heat riser or hot spot therefore, should always be eliminated.

- Engine thermostat:
  It is common in aftermarket conversions for a colder engine thermostat to be substituted for the one specified for gasoline. There are a variety of reasons and logic given for this practice but any small benefits are usually outweighed by the loss of heater and defroster performance and engine efficiency. Chrysler specifies the standard temperature (gasoline) thermostat for its propane vehicles.

- Spark plugs:
  A colder range spark plug is usually installed in aftermarket conversions. The reason given for this is that spark plug nose temperatures are hotter when using propane than when using gasoline. This is not always true; the tip temperature, and therefore the ideal heat range, depends primarily on the type of service, the fuel-air ratio, and the spark advance schedule used on the particular application. There is seldom any reason to use spark plugs more than one heat range colder (if required at all) because spark plug heat ranges are generally very wide and overlap each other considerably.

  Although aftermarket installers and propane fuel system manufacturers indicate that propane requires higher plug voltage than gasoline, and therefore requires a narrower spark plug gap, there is no agreement among ignition experts that this is the case, and there is certainly no rule of thumb to follow. In summary the plug gap required is much more dependent on the ignition system voltage capacity and breakdown rating and on the spark timing schedule than it is on the differences between gasoline and propane ionization potential.

- Spark timing
  Because the combustion properties of propane differ from gasoline, the spark timing of an engine will usually be different for the two fuels. Every engine has its own unique requirements, dependent on many factors, and it is not possible to predict accurately without dynamometer test work exactly what timing difference is required for the two fuels. Most conversion specialists make some attempt at optimizing the spark schedule for propane, although the changes made are not always for the better (see section 4.4.1). If the conversion

is to dual fuel, the spark curve is not usually modified but there are electronic devices being marketed that override the gasoline curve when in the propane mode in an attempt at spark optimization. Most OEM manufacturers use spark timing curves developed by engine dynamometer as well as on-road testing.

- Exhaust valves and seats:
Gasoline with lead additives helps to prevent seat wear, however propane is a very dry fuel and has no additives. The use of unleaded gasoline has caused vehicle manufacturers to use hardened valve seats in their modern engines, but even unleaded gasoline provides more lubrication to the valve seats than propane, and exhaust valve and valve seat combinations satisfactory for unleaded gasoline are unlikely to be adequate for propane. Most vehicle and engine manufacturers selling propane versions of their products specify special valves and seat inserts but this is seldom done with aftermarket conversions; the cost would usually be prohibitive.

- Piston rings:
Propane engines will sometimes exhibit problems where the piston rings may not break in properly during the normal break-in period. This usually occurs when a chrome-plated compression ring has been specified for optimum ring durability on gasoline. During cold starts, liquid gasoline enters the cylinder and dilutes the film of oil on the cylinder wall permitting greater metal-to-metal contact. When propane is used, no dilution of the oil film on the cylinder wall takes place and the chrome faced ring may take a long time to seat in the bore. The problem is normally avoided by specifying softer tin-plated or molybdenum-filled rings.

Vehicles being converted from gasoline to propane seldom have any problem because they usually have sufficient usage with gasoline before conversion to seat the rings.

- Compression ratio:
Propane is a relatively high octane fuel and is capable of higher compression ratios than gasoline. Some engine and vehicle manufacturers specify a higher compression ratio to take advantage of this to improve fuel economy and power output. The cost of changing the compression ratio in the aftermarket would be prohibitive, is usually not practical, and would invalidate the vehicle manufacturer's warranty.

3.4 Engine and Vehicle Performance with Propane

3.4.1 General

The degree of satisfaction and performance that is obtained from a vehicle using propane is extremely variable and is influenced by a number of factors:

- the engine and vehicle
- the quality and engineering sophistication of the propane components
- the development of unique component calibrations for specific applications
- the quality of the installation
- the type of service in which the vehicle is used
- the climatic temperature conditions
- dual-fuel or single-fuel system

Fifty or more years ago similar qualifications could be applied to gasoline vehicles, but decades of development and competition have established basic standards of performance that a buyer expects. Propane vehicles are a long way from that stage of uniformity. Although the best compare most favourably with gasoline versions and are superior in some respects, many do not satisfy expectations under all conditions.

3.4.2 Engine Power

The power output of an internal combustion engine is determined in part by the volume of air it can breathe. When gasoline is the fuel, it enters the airstream as a liquid and displaces a negligible volume of air. Propane, on the other hand, enters as a gas, and at the chemically correct fuel/air ratio displaces about 4% of the air. Decreases of 3-5% in wide open throttle (WOT) power are often reported (Refs. 4 & 5) but deletion of intake manifold heating can virtually eliminate the loss. With gasoline compression ratio and valve timing, Chrysler's 5.2 L engine shows only a 1% power loss on (single-fuel) propane. Dual-fuel engines usually exhibit a very noticeable power loss when switched onto propane, because manifold heating is retained, ignition timing is not really optimized for propane even when a dual curve ignition system is provided, and propane mixtures are often incorrect.

If the fuel-air ratio is enriched past the optimum point, power will drop off sharply with propane, whereas with gasoline the power may remain relatively constant over a wide range of fuel-air ratios. This is because the additional propane gas displaces a much larger portion of air as compared to the additional liquid gasoline.

Since propane has excellent anti-knock properties, it is possible to increase the compression ratio of the engine over what is practical for gasoline and thereby equal or exceed the power available with gasoline.

3.4.3 Fuel Consumption

The fuel consumption figures for propane engines vary widely depending on the type of test, the quality of the installation and the general condition of the vehicle, but usually propane compares more favourably with gasoline than would be expected from an analysis of the heating values and densities of the two fuels.

On a mass basis propane has more heat units per kilogram than gasoline, 46.2 vs 43.3 MJ/kg, and one would expect propane to use 6.5% less weight of fuel than gasoline.

On a volume basis, which is how gasoline and propane are usually sold, propane has less heating value than gasoline, 23.6 vs 31.6 MJ/L. On this basis one would expect propane to use 34% more volume of fuel than gasoline.

As shown in Table 3, present generation propane vehicles perform considerably better than this. The better relative performance of the propane vehicles on the city cycle, compared to the highway cycle, is attributed to the lack of need for a choke and accelerator pump on the propane vehicles, as well as to the penalty imposed by city cycle emissions standards on the gasoline vehicles.

Although it is not common to consider fuel consumption in terms other than on a volume basis, from an energy policy standpoint it is very important to note that current level propane vehicles save energy compared to gasoline, as illustrated.

ENGINE & VEHICLE	TRANS.	PROPANE/GASOLINE FUEL CONSUMPTION RATIO			
		VOLUME BASIS		THERMAL BASIS	
		CITY	HWY	CITY	HWY
8 CYL. VAN	AUTO	1.15	1.27	0.86	0.95
6 CYL. VAN	AUTO	1.24	1.22	0.93	0.91
8 CYL. PASS. CAR	AUTO	1.29	1.33	0.96	0.99
6 CYL. PASS. CAR	AUTO	1.13	1.26	0.84	0.94
AVERAGE - ALL VEH.		1.20	1.27	0.90	0.95

TABLE 3 Propane/Gasoline CVS Fuel Consumption Ratios for Selected Early Prototype Chrysler Vehicles

3.4.4 Driveability

At normal ambients, well-designed propane vehicles have excellent driveability and response to changing speeds and loads. The quick and ready response to the accelerator is attributed to the minimal difference in inertia between the incoming fuel and air and also to the ability of propane to run smoothly with wide variations in fuel-air ratio. The response to the accelerator is often so smooth and quick that the driver gets the impression that the vehicle has more power.

At ambients below -15°C, most propane vehicles demonstrate warm-up driveability problems associated with the capacity of the vaporizer to vaporize fuel before the engine coolant has been warmed up. However the use of a block heater has been shown to cure warm-up problems down to temperatures of -35°C and probably to the lowest temperature that fuel can be delivered to the converter by tank vapour pressure. Propane-fueled vehicles are unlikely to operate below the boiling point of propane (-42°C), unless the fuel contains lower boiling point constituents such as ethane, or unless some other means are used to deliver the fuel to the vaporizer.

3.4.5 Durability

With propane engines, cylinder bore and ring wear is usually less than with gasoline. Combustion chamber deposits are also normally less than with gasoline and

consist mainly of lube oil additives. Propane itself has no additives, burns very cleanly and contributes practically nothing to combustion chamber deposits. As a result, there is very little chance of spark plug fouling. Whether spark plugs last longer than when using gasoline is not completely clear and more fleet testing needs to be carried out.

It is often claimed that engine oil lasts longer with propane but the claim is highly questionable and limited data to date indicates that this is not true. This subject is discussed more fully in section 4.7.

The major durability problem with propane engines is exhaust valve seat wear. The wear is most aggravated with high speed service and exhaust valves and seats designed for unleaded gasoline are unlikely to be satisfactory for use with propane. More research is necessary and the subject is reviewed in more detail in section 4.6.2. Intermittent use of leaded fuel on a dual-fuel vehicle will considerably lessen valve seat wear due to the lubricating properties of the lead compounds used.

3.5 Conclusions and Recommendations

(1) Uniformity of regulations across Canada would be helpful to the manufacturers of propane equipment and vehicles.

(2) Aftermarket conversions of vehicles from gasoline to propane have only limited opportunities for optimization because of design constraints, economic practicality and the possibility of invalidating the vehicle manufacturer's warranty.

(3) Overall quality and performance of vehicles converted from gasoline to propane are widely variable.

(4) High exhaust valve seat wear can be expected to occur on most aftermarket conversions with resultant early failure of the cylinder head.

4. ENGINE OPTIMIZATION FOR PROPANE

4.1 Overview

In the early days of internal combustion engines, gaseous fuels such as coal gas were commonly used, but the spark ignition engine has evolved and developed together with gasoline. Neither the engine nor the fuel can be considered in isolation and the properties and performance of one are mutually dependent on those of the other. Indeed much of the evolution of both gasoline and the S.I. engine has been sponsored and promoted by the Coordinating Research Council, the organization which reflects the combined interests of the United States motor vehicle industry and the petroleum industry. It is not surprising, therefore, that when alternative fuels are considered, we find that the new fuel and the engine may not be in complete harmony with one another. That turns out to be the case when we look to propane as an alternative fuel.

While the world price of crude oil remained low there was little incentive to explore alternative types of fuel. As recently as ten years ago, crude oil was less than $5.00 U.S. per barrel.

All through the 1970's the vehicle manufacturing companies were dedicating a great deal of their resources and manpower to meeting increasingly stringent exhaust emission and safety regulations. The rise in fuel costs since 1973, accompanied by fuel economy regulation, forced the vehicle manufacturers to devote even greater resources and manpower to downsizing cars and trucks while increasing the efficiency of their engines. The task of addressing alternative fuels, therefore, was put aside and until the present time only a modest effort has been directed at alternative fuels or to optimizing engines for their use; vehicle manufacturers had more pressing demands. As a result the development of propane conversion equipment has been an aftermarket enterprise which has developed a growing catalogue of shelf items being applied to a large variety of types and sizes of gasoline engines. In the meantime, the distribution of automotive propane has been growing to keep pace with the volume of aftermarket conversions.

In today's environment of customer expectation and government regulation, vehicle performance can be considered a three-legged stool which must be kept in balance. The three interdependent requirements which must be met are driveability, fuel economy and exhaust emission control. Furthermore, there is a great interdependence between the engine design parameters affecting the three requirements. Such parameters, among others, are

compression ratio, spark timing, fuel-air ratio and valve timing. In view of all these factors, it would be highly fortuitous if a vehicle and engine system designed for gasoline were able to achieve optimum performance by the application of off-the-shelf propane equipment without substantial modification and adjustment of the basic system.

Optimization of engines for use with propane requires not only a greater understanding of fundamental combustion characteristics of propane, but also a detailed development of engines on an individual basis. The new modern low displacement, high speed, high load engines coming on the market today may not react to propane in the same way as large displacement, relatively low speed, heavy truck and industrial engines which have been the big users of propane in the past.

Engines will continue to be designed primarily for gasoline and modifications for use with propane, even by vehicle and engine manufacturers, will have to be evaluated in terms of design and cost limitations.

This, then, is the background against which we take a detailed look at optimizing an engine for propane.

4.2 Compression Ratio

4.2.1 General

In evaluating the benefits to be derived in an engine by increasing the compression ratio, it is helpful to look at the theoretical and practical limitations.

The efficiency of an idealized constant volume or Otto cycle using a perfect gas in a perfect engine is a function of compression ratio only and independent of other variables (Ref. 6). On the other hand, in a real engine using imperfect mixtures of fuel and air, the efficiency obtainable by compression ratio increase alone is limited and is also affected by fuel-air ratio.

Figure 4 illustrates how the efficiency of an ideal air cycle increases continuously with an increase in compression ratio, but that in a real engine using imperfect fluids and with heat losses through the cylinder walls, the indicated efficiency reaches a peak at some point between 13:1 and 18:1 compression ratio.

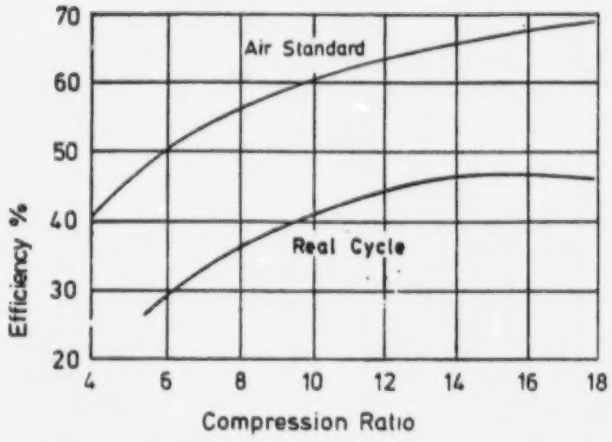


Figure 4 Comparison Of Efficiencies Of A Constant Volume Air Cycle And A Real Fuel-Air Cycle

Efficiency improvement through increases in compression ratio is manifested by a gain in power output and decreased fuel consumption, usually measured as brake specific fuel consumption (BSFC) mass of fuel per unit of work.

Figures 5 and 6 demonstrate the power and BSFC improvement at WOT achieved in one particular 413 cu. in. V8 engine using gasoline for fuel (Ref. 5) when the compression ratio was increased from 7.5:1 to 9.9:1 and again to 11.5:1. At 9.9:1 compression ratio power increased 10% on average while BSFC was reduced by 7%. At 11.5:1 compression ratio, the power gain had risen to 12% and the BSFC declined to 10% below the standard compression ratio. It should be noted that in order to obtain data at 9.9:1 and 11.5:1 compression ratios, super premium fuel was needed to avoid detonation and it would not be possible to use these higher ratios in practice with commercially available gasoline. On the other hand, as will be reported later, this engine operated without engine knock at 7.5:1 and 9.9:1 compression ratios when using propane with its superior anti-knock properties. At 11.5:1 compression ratio, propane also required an octane improver.

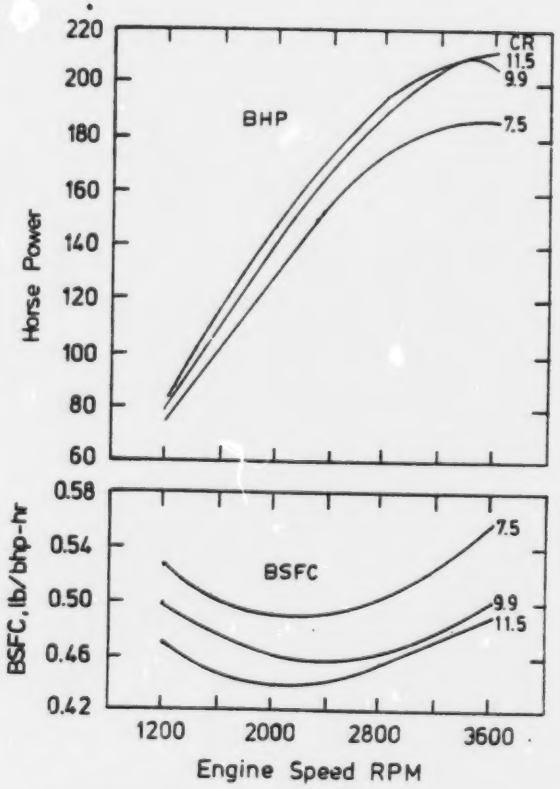


Figure 5 Effect Of Compression Ratio On Performance —Gasoline ; 413 CID Engine ; WOT (Ref. 5)

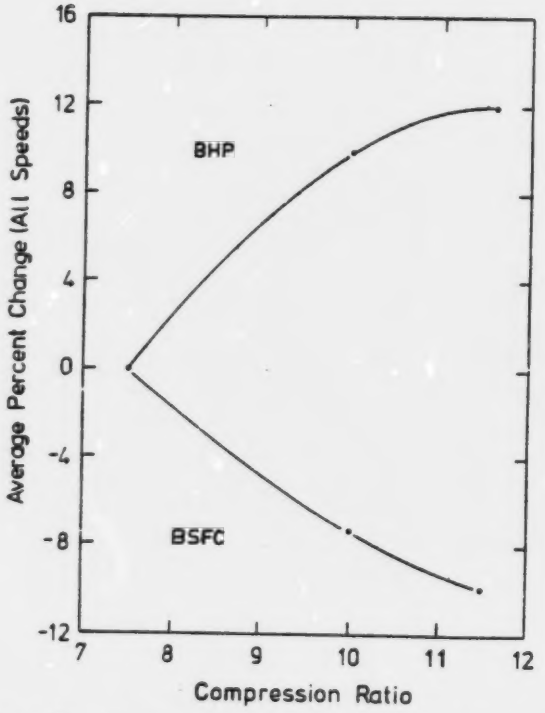


Figure 6 Percent Change In Power And Fuel Consumption With Compression Ratio (Ref. 6)

In a practical sense, in any spark ignition engine, the compression ratio is limited by the onset of detonation sometimes called spark knock or "ping". The noise in a passenger car is objectionable and detonation may cause overheating of spark plugs leading to preignition and serious engine damage. This practical limit for a given engine is termed the knock limited compression ratio (KLCR) which is dependent primarily on the engine design and the anti-knock quality of the fuel used. Figure 7 illustrates the typical relationship between KLCR and the fuel octane. The values shown will be different for different engines and fuels and are shown only to give an indication of the general relationship between octane quality and knock limited compression ratio.

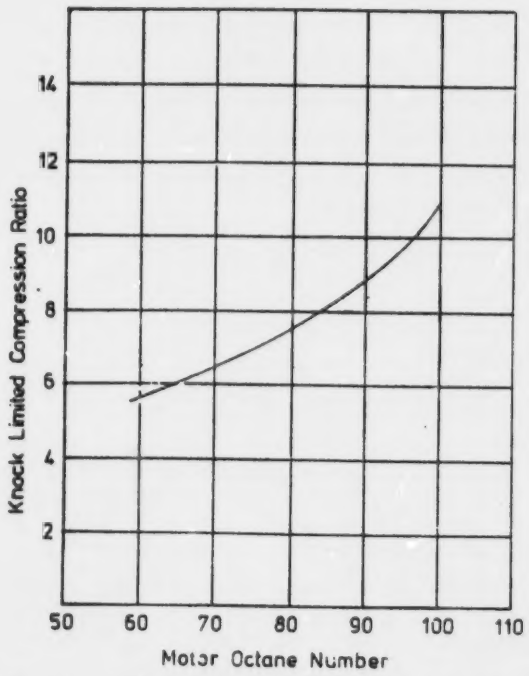


Figure 7 Typical Relationship Between KLCR Of An Engine And Octane Rating Of The Fuel

The spark ignition engine and gasoline have evolved and matured together; the performance of the engine and the quality of the fuel used are so closely interrelated that it is difficult to discuss either of them in isolation. The power output and fuel consumption are highly dependent on the compression ratio, and this in turn depends on the anti-knock quality of the fuel and combustion chamber design.

Figure 8 shows the trend of average compression

ratios in North American car engines and the parallel trend of gasoline octane quality (Ref. 7). A comment on the background for the changes may be helpful.

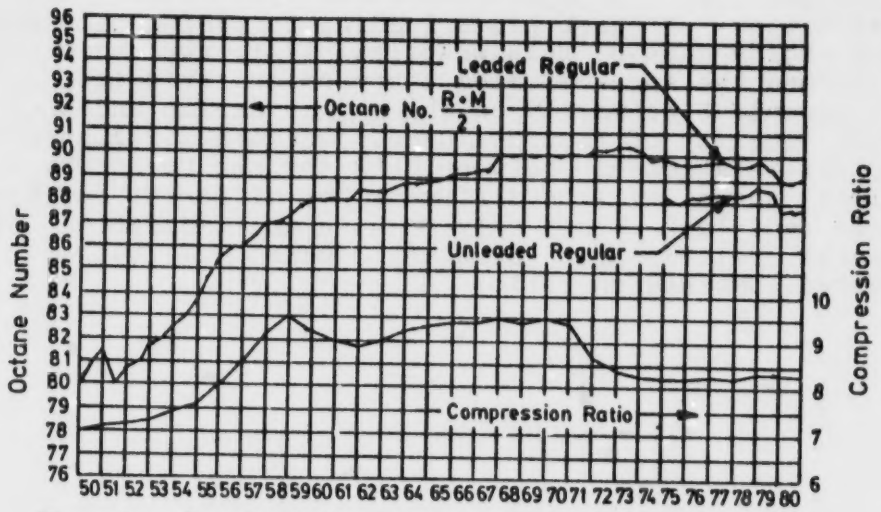


Figure 8 Trends Of Average Compression Ratio And Regular Grade Octane Ratings In USA.
(R+M)/2=Average Of Reseach And Motor Octane For Regular Grade Gasolines (Ref.7)

The post-war demand for large, roomy, powerful cars led to a steady increase in compression ratio through the 1950's. In the 1960's the problems of air pollution in highly populated areas from industrial and automotive emissions led to regulations controlling emissions from both these sources. The stringent 1975 model year emission reduction demands of the U.S. Clean Air Act of 1970 required the use of catalytic converters which in turn necessitated the use of unleaded gasoline. Removal of lead additives was forecast to result in reductions in the octane levels of gasoline in the later half of the decade. In anticipation of this trend, motor vehicle manufacturers began to reduce compression ratios in 1971 to avoid potential knock related problems, while concurrently introducing induction hardened exhaust valve seats on cast iron heads.

The 1970's were further affected by shortages of oil and rapidly escalating prices, and the oil embargo of 1973 precipitated a completely new direction for the North American automotive industry. A new generation of compact and sub-compact fuel-efficient vehicles from both domestic and foreign manufacturers became the trend. Lower fuel consumption by every means possible was the order of the day and compression ratios are now commencing to edge up to the

maximum that can be tolerated by commercially available gasoline.

The anti-knock quality of propane is one of its most attractive properties and gives us the opportunity to increase compression ratios beyond what is permissible with gasoline and thereby improve power and lower fuel consumption. Table 4 shows minimum octane values of automotive grade propane compared to typical values for regular and premium grade gasolines available in Canada.

	CGSB GRADE 1 PROPANE	PREMIUM UNLEADED GASOLINE	REGULAR UNLEADED GASOLINE
RESEARCH OCTANE NO. (RON)	108	96.5	93.5
MOTOR OCTANE NO. (MON)	95	86.4	84.0

TABLE 4 Octane Values of Automotive Propane and Gasoline

Shell International (Ref. 8) has evaluated the power output of a vehicle using a 9.1:1 compression ratio. It was tested at that ratio with gasoline and with a dual-fuel LPG (propane) conversion not optimized for propane. It was then optimized for propane using a compression ratio of 11:1. Figure 9 shows that the unoptimized dual fuel version gave 3-9% less power than with gasoline at the same compression ratio. However, when the compression ratio was raised to 11:1 and the engine optimized for propane, a gain of 5% over the standard gasoline version resulted.

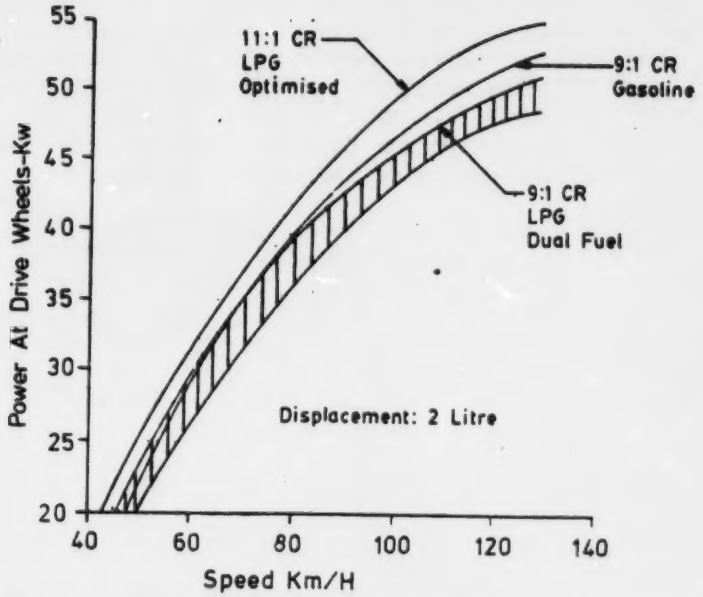


Figure 9 Comparison Of Power Output From Gasoline Dual-Fuel LPG And Dedicated High Compression LPG Engine (Ref. 8)

Figure 10 shows the improvement in power output and BSFC when the compression ratio of an engine is increased from 7.5:1 to 9.9:1 and 11.5:1 using propane. These data are taken from the same source (Ref. 5) as Figure 5 and are compared to the performance with gasoline at the standard ratio of 7.5:1 which would be close to the KLCR for that engine with regular gasoline. At 7.5:1 with propane the power loss was approximately 3.5%; at 9.9:1, the power gain compared to gasoline at the standard compression ratio was 5% and at 11.5:1, the gain was 9%.

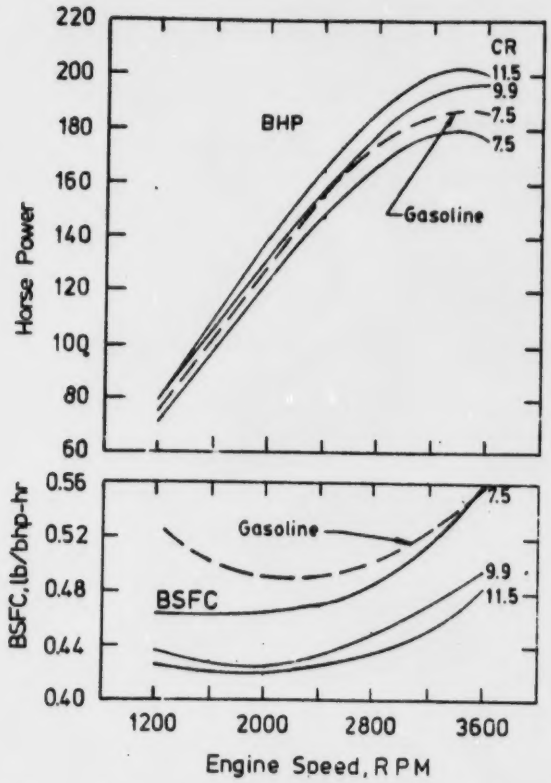


Figure 10 Effect Of Compression Ratio On Performance —LPG; 413 CID Engine; WOT (Ref. 5)

When using propane, the BSFC was lower at all ratios than when using gasoline at the standard ratio of 7.5:1. The improvement compared with the standard gasoline engine was: at 7.5:1 - 4%, at 9.9:1 - 12.5%, and at 11.5:1 - 15%.

BSFC is measured as mass of fuel used per unit of energy output. If we consider it on the basis of energy used per unit of energy output then propane at 7.5:1 CR uses 2% more than gasoline; at 9.9:1, 7% less; and at 11.5:1, 9% less.

These data are representative of findings by other investigators (Refs. 9,10,11,12,13).

There are some cases where the power output of an engine optimized for propane by means of spark advance curves, fuel-air ratio control, and reduced intake charge temperatures, will equal or slightly exceed the power output with gasoline at the same compression ratio (Refs.

9,14). In almost all cases the BSFC with propane is superior to gasoline largely because of its higher heating value per unit weight and probably, in part, because of improved fuel-air mixing and distribution.

Increasing the compression ratio of an engine for use with propane is clearly one of the best ways to improve power output and lower fuel consumption. In most cases a modest increase can be accomplished without major redesign or retooling of the engine. The compression ratio is increased by reducing the volume of the combustion chamber and depending on the particular engine it can be achieved in one or more ways:

- change the shape of the piston crown
- lower the height of the cylinder block by milling the surface which mates with the cylinder head
- mill the cylinder head surface which mates with the cylinder block
- make casting changes to the cylinder head to decrease the combustion chamber volume

All of these techniques have been shown to be economically feasible by OEM manufacturers. The amount of compression ratio increase and the method of achieving it will depend on each individual engine and in turn is determined by:

- the design of the engine
- the design of production tooling.

One or the other of these two factors is likely to be the item which limits compression ratio increase on the basis of technical or economic feasibility. On the other hand, when the compression ratio is increased, the cylinder pressures are proportionately increased, imposing higher stress on pistons, bearings, and engine structure. Cylinder head gasketing can also be a problem. In all cases, the manufacturer has to assure himself that engine durability is not sacrificed.

4.2.2 Conclusions and Recommendations

(1) Increasing the compression ratio of an engine for use with propane can be a practical, cost effective method of improving power output and reducing fuel consumption.

(2) Fuel consumption decreases and power output increases are very significant for initial compression ratio increases beyond current gasoline levels, but diminish rapidly with further increments, particularly in the case of fuel consumption.

(3) The decrease in fuel consumption resulting from a higher compression ratio can be further enhanced by taking advantage of the increased power output to use a lower overall drive ratio in the vehicle.

(4) The increased power output resulting from higher compression ratio also provides the opportunity to modify the torque curve through changes in valve timing to give better overall driveability.

4.3 Carburetion

4.3.1 General

The purpose of carburetion, whether for gasoline or propane is the same - to meter and mix fuel and air so as to provide the correct fuel-air ratio over the full range of speeds and loads including start and warmup. In general, the optimum fuel-air ratio at any given speed is that which will develop the required torque, and therefore power, with the lowest fuel consumption consistent with reliable operation.

The task of a gasoline carburetor is more difficult than a gaseous fuel carburetor because it is necessary for the liquid fuel to mix with the air and vaporize in the intake manifold and cylinder before it ignites. During steady state operations an equilibrium is established in the intake system such that the average vapour fuel-air ratio being ignited in the cylinders is equal to the liquid fuel-air ratio supplied by the carburetor. During transient conditions, however, the vaporized fuel-air ratio being burned in the cylinders is not necessarily the same as the liquid fuel-air mixture being delivered by the carburetor for the following reasons: (Ref. 6).

- vaporization of the fuel may be incomplete when ignition takes place

- the quantity of liquid fuel in the manifold may be increasing or decreasing

As a consequence, a gasoline-powered engine under many conditions will require rich mixtures at the carburetor in order to ensure a suitable mixture in the cylinder. This is particularly evident in starting a cold engine when a choke is necessary to give an extremely rich liquid fuel-air ratio in order to obtain enough vaporized fuel in the cylinder for combustion to take place.

Furthermore, the composition of the fuel received by each cylinder may be different from other cylinders and different from the fuel in the carburetor bowl. This is

because partial vaporization causes separation of the more volatile fractions of the fuel from the high boiling point fractions. This not only causes variations in fuel-air ratio between cylinders, but the knock characteristics of the fuel can also vary from cylinder-to-cylinder because each fraction of the gasoline has a different octane rating.

In contrast, the propane carburetor meters fuel in its gaseous state and since there is no unvaporized fuel in the manifold or cylinder, the mixture being ignited is for practical purposes the same as being delivered by the carburetor. No choke or accelerator pump is required. Cylinder-to-cylinder distribution can be uniform, and because automotive propane is essentially a single component fuel (90% propane min.), the octane value of the fuel reaching each cylinder is consistent.

Contrary to widely held belief, however, cylinder-to-cylinder distribution is not always uniform with propane and is dependent on the degree of mixing in the carburetor and intake manifold.

Figure 11 (Ref. 15) illustrates the fuel-air ratio distribution in a six-cylinder engine using gasoline and butane. Distribution with butane shows substantial improvement over the distribution with gasoline, but not until modifications were made to improve mixing, did distribution with butane approach uniformity.

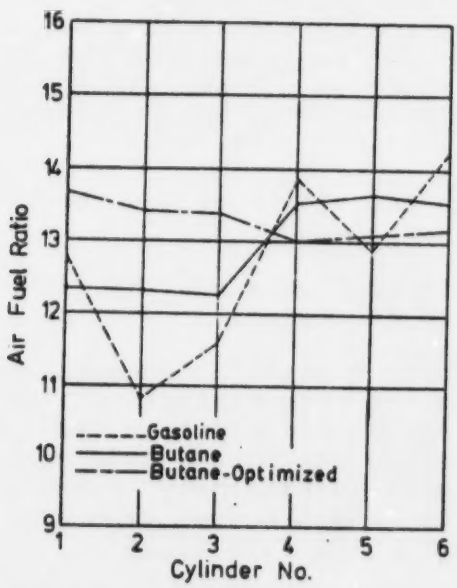


Figure 11 Comparison Of Liquid Fuel (Gasoline) vs Gaseous Fuel (Butane) On Mixture Distribution (Ref. 15)

Fuel distribution studies by H.T.C.Yu. (Ref. 16) also demonstrated that complete vaporization of the fuel did not automatically guarantee good distribution. His tests using propane showed wide variations in fuel-air distribution depending on how the propane was introduced into the air stream and the method of inducing turbulence and mixing (Table 5).

PROPANE JET LOCATION	INJECTION PRESSURE (in. water)	MEAN A/F	A/F SPREAD
1. Standard Gasoline Carb.	---	17.7	2.4
2. Into Venturi	1.1	17.8	7.2
3. Into Venturi Plus Mesh Screen Below Throttle	1.1	18.4	5.4
4. Tangentially Into Venturi	4.4	17.8	1.8
5. Into 3 in. dia. Hose 5 ft. Long Attached to Carb. Air Horn	1.0	17.8	1.8
6. Same as 5 plus Induced Swirl After Venturi	15	18.4	0.3

TABLE 5 Air-Fuel Mixing Results with Propane (Ref. 16)

Chrysler Canada Ltd. has also made distribution measurements on a V8 engine using both gasoline and propane. The results determined at wide open throttle over the speed range 1200-4000 RPM are shown in Figure 12. The distribution with propane was better at lower RPM but at higher speeds there was no improvement over gasoline.

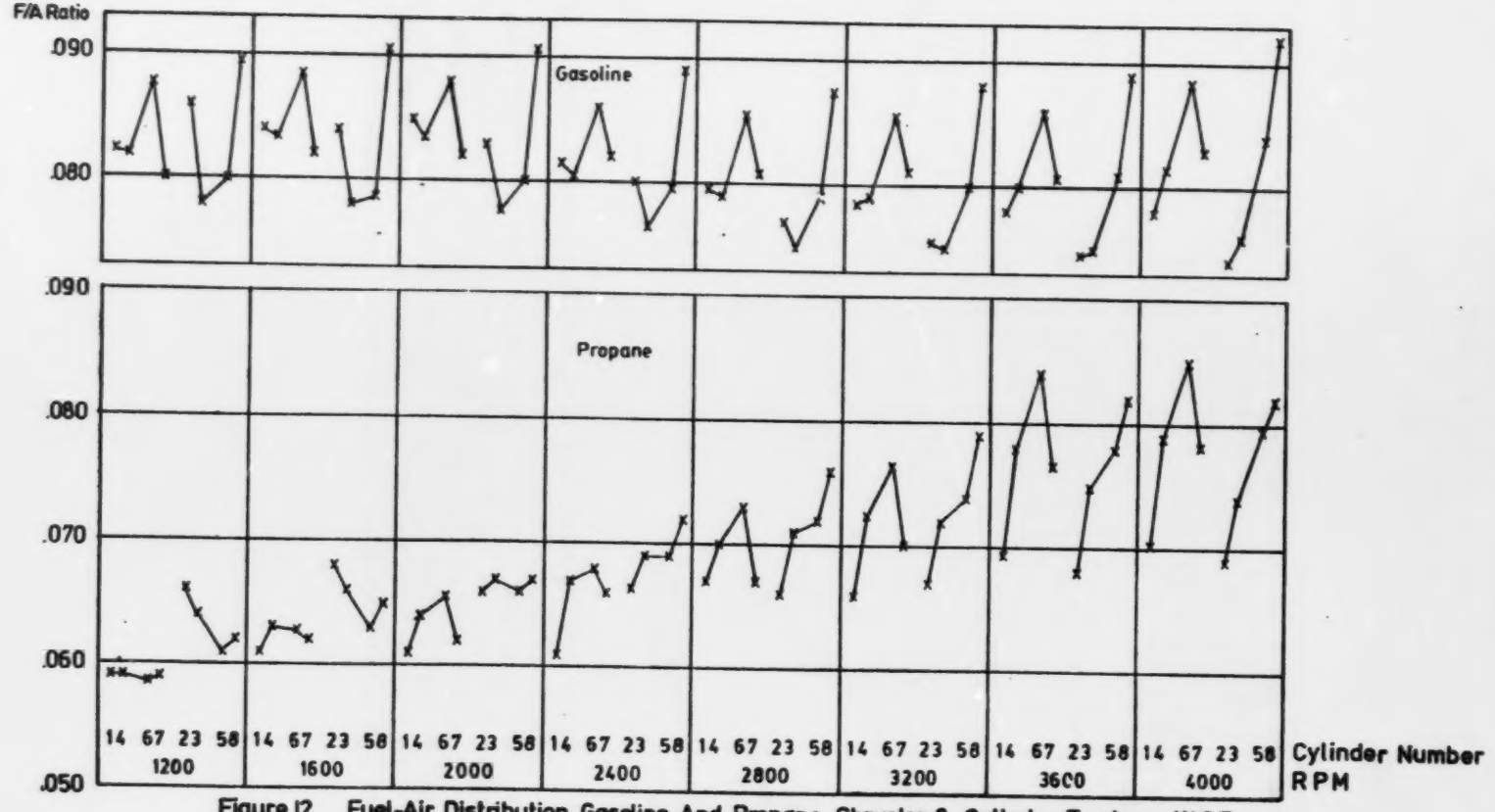


Figure 12 Fuel-Air Distribution, Gasoline And Propane - Chrysler 8-Cylinder Engine - W.O.T.

In order to assist the vaporization of gasoline, heat is added to the intake manifold by means of an exhaust gas or water heated hot spot. This is not required with propane since it is already a gas and indeed heating the intake manifold expands the gas and lowers the volumetric efficiency, thereby reducing the maximum power available. This is clearly demonstrated when a dual-fuel gasoline/propane engine, operating in the propane mode, is compared with a straight propane version of the same engine. The dual-fuel version which retains intake manifold heat always exhibits less power than the straight propane version with manifold heat deleted. The influence of manifold heat was demonstrated by Blalock and Little (Ref. 17). Figure 13 shows the effect of hot vs. cold manifold on WOT power and BSFC. The cold manifold also permitted a leaner fuel-air mixture at WOT (Figure 14).

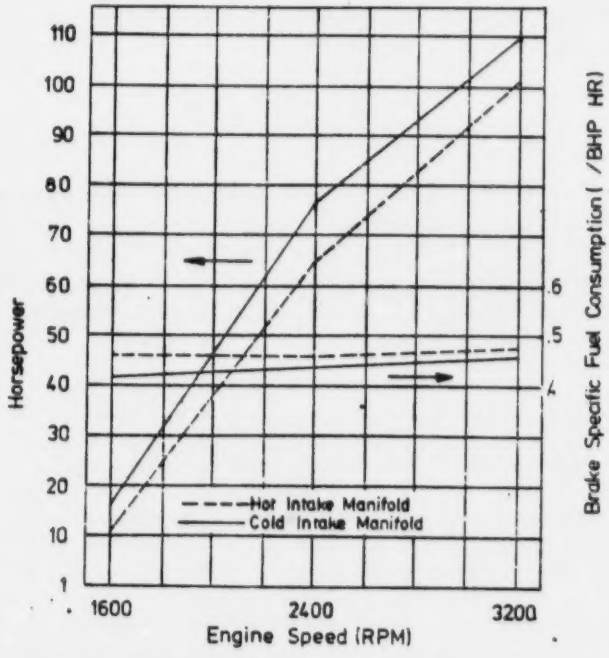


Figure 13 Hot Versus Cold Intake Manifold—LPG; V 6 478 CID Engine; LBT Fuel Control; MBT Spark Control; WOT (Ref. 17)

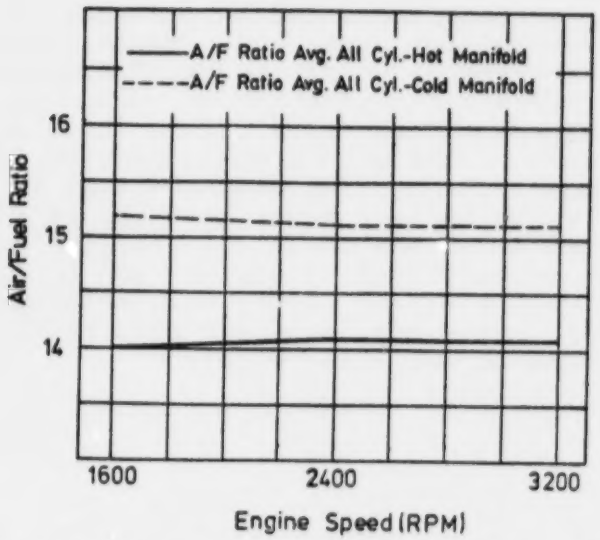


Figure 14 Hot Versus Cold Intake Manifold—LPG ; V-6 478 CID Engine:LBT Fuel Control;MBT Spark Control;WOT (Ref.17)

The more general affect of intake manifold fuel-air mixture temperature on power output of a propane-fueled engine was investigated by Harris and Hummel (Ref. 18). Their findings (Figure 15) demonstrate how power output drops as air-fuel mixture temperature increases.

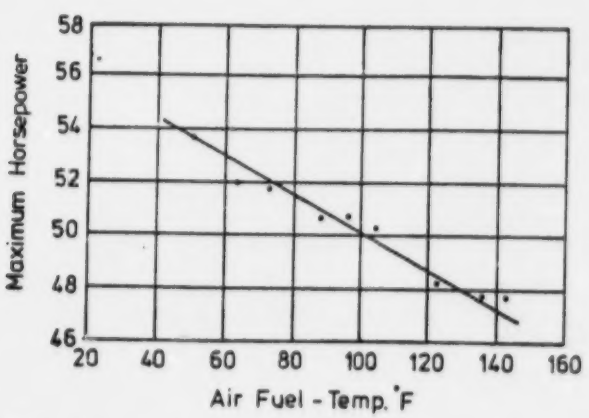


Figure 15 Variation Of Power with Temperature Of Air-Fuel Mixture (Ref.18)

4.3.2 Fuel-Air Ratio

Like compression ratio, fuel-air ratio has a profound effect on power output and engine efficiency. The fuel-air ratio is in turn influenced by the molecular structure of the hydrocarbon fuel used and by the size of the hydrocarbon molecule. For straight chain aliphatic hydrocarbons, the size of the molecule is directly proportional to the percentage of carbon in the molecule.

The stoichiometric or chemically correct mixture increases as the carbon percentage increases. This means that for perfect combustion, gasoline requires a richer fuel-air ratio than propane -- 0.0686 vs. 0.0638.

Paul and Popovich (Ref. 19) investigated the fuel-air requirements of a number of hydrocarbons for maximum power and minimum fuel consumption. Included in their study was propane, n-butane, isopentane, isooctane, and gasoline. Their findings are shown in Figures 16 and 17 and since their work was carried out on a single cylinder engine, it eliminated the variables associated with cylinder-to-cylinder distribution of multi-cylinder engines.

In Figure 16 , percent of maximum power is plotted against air-fuel ratio for each fuel tested and in Figure 17 percent of minimum fuel consumption is plotted against air-fuel ratio. For optimum power the air-fuel ratio ranged from 15.5 for propane to 12.9 for gasoline and for minimum fuel consumption the ratio for propane was 17.9 and for gasoline 16.0. The air-fuel ratios for the other fuels fell between the values for propane and gasoline and were arranged in ascending order of percent carbon in the fuel.

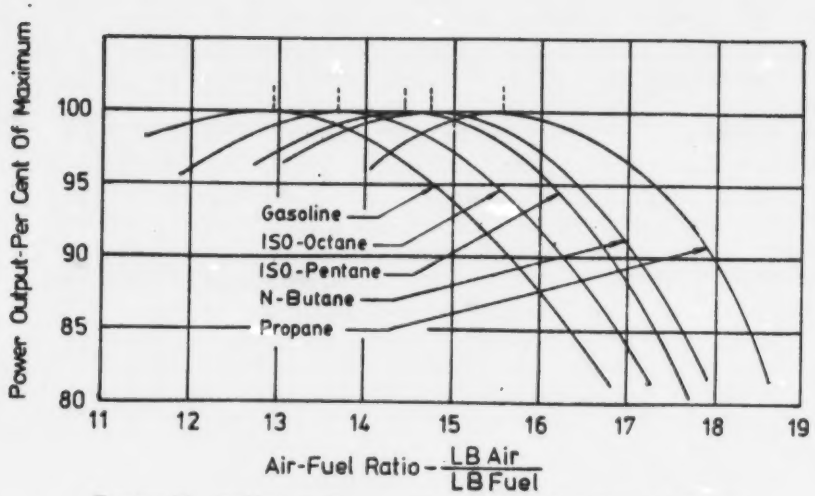


Figure 16 Optimum Power Air-Fuel Ratios For All Fuels Investigated (Ref. 19)

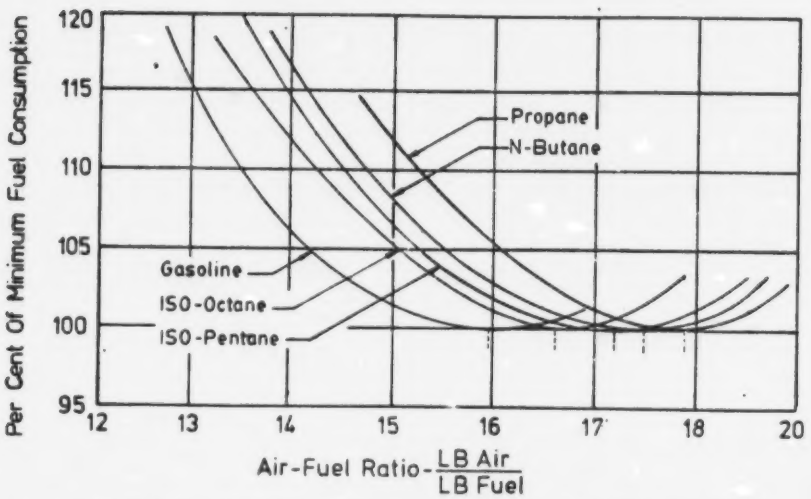


Figure 17 Optimum Economy Air-Fuel Ratios For All Fuels Investigated (Ref. 19)

The maximum power and minimum fuel consumption values for Figures 16 and 17 were plotted by Paul and Popovich against the respective carbon contents of the fuel molecules. These values are shown in Figure 18 along with the stoichiometric air-fuel ratios for each of the fuels.

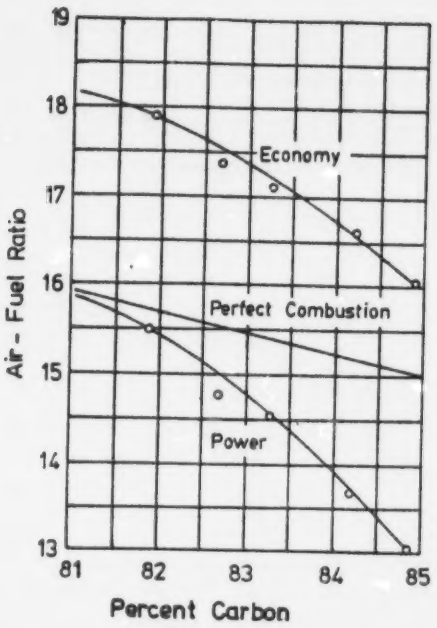


Figure 18 Optimum Air–Fuel Ratios Vs Percent Carbon Contained By Each Fuel.
Points From Left To Right In Order
Represent Propane, Butane, Pentane, Octane And Gasoline
(Ref. 19)

Since the carbon content of a hydrocarbon series is proportional to the molecular size, it is apparent that with decreasing molecular size the air-fuel ratio for maximum performance approaches stoichiometric. From this, one might speculate that the maximum power mixture for methane, the lightest hydrocarbon, would be stoichiometric. In this series of tests, the maximum power equivalence ratio Fr = 1.01 for propane and for gasoline Fr = 1.15.*

The shape of the economy curve is similar to the power curve. As the fuel molecules become smaller, the percent of excess air over stoichiometric increases and for propane this amounted to two air-fuel ratios (15.7 to 17.9) giving an equivalence ratio, Fr=0.887. For gasoline, the minimum consumption mixture was only one air-fuel ratio leaner than stoichiometric (15.0 to 16.0) for an equivalence ratio of Fr=0.938.

*(Fr = Fa/Fc where Fa = actual fuel-air ratio;
Fc = chemically correct fuel-air ratio)

A further examination of Figure 16 shows that propane is less tolerant than gasoline with respect to mixtures richer than necessary for maximum power. One ratio rich for gasoline drops maximum power approximately 1 1/2 % while one ratio rich for propane drops power about 2 1/2 %. On the other hand, an examination of Figure 17 shows propane more tolerant than gasoline for mixtures richer than required for minimum fuel consumption. For propane, 2 ratios rich increases consumption approximately 5% while for gasoline 2 ratios rich increases consumption about 7%.

These data can be summarized as follows:

- The equivalence ratio Fr for propane is leaner than for gasoline for both maximum power and minimum fuel consumption and for maximum power the propane mixture approaches stoichiometric.

- Mixtures richer than required for maximum power cause a more rapid fall in power with propane than with gasoline.

Other investigators (Refs. 5,11,20.21,22) have confirmed that propane requires leaner equivalence ratios than gasoline and mixtures richer than required for maximum power should be avoided. Mengelkamp and Hudson, on the other hand, found maximum power equivalence ratios of 1.1-1.3 (Ref. 23). In this study, no values for gasoline were determined and so no comparison can be made. It is probable that with multi-cylinder engines, cylinder-to-cylinder fuel-air distribution strongly influences how lean the mixture can be.

These data demonstrate the problems that can be encountered if lessons learned about gasoline air-fuel ratios are applied without modifications to propane-fueled vehicles.

4.3.3 Present Propane Carburetion Systems

The ability of spark-ignited engines to tolerate very lean and very rich propane fuel-air ratios is propane's best and perhaps also its most detrimental feature. Because a propane engine will operate smoothly at fuel-air equivalence ratios which would stall or even destroy a gasoline-fueled engine, a large number of crude propane carburetion systems have appeared on the market. At the present time, no currently available "off the shelf" system will provide correct fuel-air ratios for all of the engine's various operating conditions. Only a few of these systems can be tailored after installation to optimize an individual parameter or to provide a good compromise between two parameters (such as fuel economy and power). In most cases the aftermarket installer has no incentive to make the required adjustments and/or modifications. Few

conversion shops (if any) can afford the luxury of individually tailoring a unique carburetion system for each of the various engine/vehicle combinations they encounter. In spite of this, conversions are readily accepted by the consumer because he is usually not aware of how poor the fuel calibration is. More often than not, if poor fuel economy and lack of performance is noticed, it is attributed to propane motor fuel in general, not to the quality of the conversion or conversion hardware.

There are basically three different types of propane carburetion systems in common use today: the venturi, the air valve, and the mechanically driven fuel metering valve. Virtually all of these systems use a fuel vaporizer which delivers gaseous propane to the carburetor at essentially constant pressure. Some systems modify this pressure to achieve leaner cruise fuel-air ratios. The outlet pressure is in most cases set to deliver fuel at slightly below atmospheric pressure (approximately -1 to -5 cm of water column -- see section 4.3.4 on the Pressure Regulator/Vaporizer).

The venturi designs are similar to conventional gasoline carburetors. The most significant difference relates to the size and location of the fuel nozzle(s). The typical propane venturi has a number of machined holes drilled around the periphery of the venturi and connected to an internal propane feed passage. These holes are calibrated so as to perform both the fuel metering function and the fuel-air mixing function. (At least one major carburetion manufacturer separates these functions in the same way as in a gasoline carburetor and uses an internal propane metering jet and large dual periphery nozzles.) In order to compensate for production variations in the size of the drill holes located in the venturi, the carburetors that use these holes for fuel metering usually also have a gate valve (sometimes called a power valve) placed in series with the fuel flow. The valve is used to manually trim the fuel-air ratio by restricting the flow of fuel. Low air flow at engine idle does not provide sufficient venturi signal for adequate idle fuel flow and, for this reason, the venturi propane carburetor often incorporates a pressurized (higher than atmospheric) idle fuel circuit that is controlled via an adjustable needle and seat assembly built into the carburetor or vaporizer. The pressurized idle fuel is normally drawn from the primary pressure stage of the vaporizer and enters the engine at the carburetor or sometimes directly via a vacuum connection on the intake manifold. Some versions that enter at the carburetor do so via an idle hole and a transfer slot at the throttle blades with the intention of providing a progressive transition between idle and main fuel metering systems.

Assuming that the original design of the flow characteristic is reasonably close to correct, the main drawback of the venturi carburetor at present concerns part-to-part variations in the flow characteristics caused by the degree of precision required in the venturi drill holes. A central metering jet simplifies this problem somewhat in that it is easier to produce a consistent flow characteristic when only one orifice is involved.

The air valve carburetor is essentially a mechanical air flow meter. A fuel metering valve is connected to a spring-loaded vacuum diaphragm which moves the valve in direct proportion to air flow through the carburetor. The contour of the fuel metering valve can be varied to determine the air-fuel ratio at any given air flow rate. The primary advantage of this arrangement is that the flow characteristic need not be a linear function of air flow and can be lean at cruise air flow rates and rich at the high air flow rates that normally correspond to high load. The disadvantage is that a given flow rate of air can be required by many different operating conditions that each require quite different air-fuel ratios. For example, the air flow rate required for a 100 km/h cruise may be identical to that during a low speed low RPM acceleration, but the cruise requires a much leaner mixture than does the low speed acceleration. The correct fuel mixture at idle is achieved through two interacting mechanisms. First, the fuel-metering valve is shaped to provide a richer-than-required fuel mixture at idle air flow rates, and second, an air bypass system is adjusted to vent air past the metering system, thereby leaning the mixture to the desired ratio. A gate valve is normally placed in series with the fuel line between the vaporizer and carburetor and is used to trim the fuel-air ratio at high engine loads for peak power output.

A number of recent carburetors (and a few older designs as well) use a mechanically driven fuel metering valve. These systems vary considerably in mechanical design and configuration but the basic operating principle is the same. A propane metering valve is driven mechanically or electrically by a mechanism that responds directly or indirectly to one or more engine parameters. For example, several designs incorporate a drag link arrangement between the throttle shaft and metering valve to open the valve in proportion to throttle opening. Some designs that use the linkage also compensate for the difference in air flow that occurs at different engine speeds for the same throttle opening by means of a venturi in the air stream. A rather unique design uses an electric motor controlled by various electrical sensors that monitor different engine parameters to open the fuel metering valve.

4.3.4 Future Propane Carburetion Systems

The major effort in propane fuel system development today is being directed toward improvements in presently available carburetion systems. There is also some research being done on oxygen feedback systems, electronic open loop control systems and liquid fuel injection.

Most carburetion manufacturers are understandably reluctant to invest large amounts of tooling money in totally new carburetor designs. For this reason, most of the improvements in current designs are appearing as modifications and/or auxiliary devices added to older designs and intended to perform such functions as improved control of fuel-air ratio, power enrichment, and leaner cruise mixtures. Typically, these devices function by modifying the vaporizer outlet pressure or by adding additional fuel metering functions.

In order to meet the increasingly stringent gasoline exhaust emissions standards in the U.S., most automakers have found it necessary to adopt an emissions control system utilizing a three-way catalyst. The narrow band of exhaust gas composition which gives efficient conversion of all three constituents (HC, CO, NOx) in a three-way catalyst requires much more precise control of the fuel-air mixture being delivered to the engine than could be obtained with the gasoline carburetor as it has been developed prior to this time. The precision was achieved by means of an oxygen sensor in the exhaust stream which generates a voltage in the absence of oxygen. The associated electronics monitor the output voltage and adjust the fuel-air ratio so that the sensor's output is maintained at the point where it is constantly switching on and off. This point corresponds to a stoichiometric fuel-air ratio. The oxygen sensor is independent of the fuel used and it is not necessary for the catalyst to be present when using a feedback system. Feedback systems can and have been used experimentally with cars using propane/LPG. If propane-butane fuel blends are used, the feedback system will automatically compensate for the fuel hydrocarbon content. However, fuel-air ratios are held at stoichiometric and do not permit richer mixtures if required for maximum power or leaner mixtures for maximum economy. In addition, a mechanism must be provided for fuel control during engine warm-up since the oxygen sensor will not function until it reaches operating temperature.

The limitations of the feedback system using an oxygen sensor can be overcome by using an electronic open loop control system. The design uses the same type of fuel control system as used in a feedback system except that no measurements are made of exhaust gas composition. Instead, the system uses inputs from various engine sensors (vacuum, RPM, temperature, throttle position, etc.) and then calcu-

lates the correct air-fuel ratio according to a control program in an onboard engine computer. The primary advantage of this type of system is that the control program can be designed to provide the ideal fuel-air ratio for virtually all engine requirements. It can also be programmed to compensate for hardware deficiencies, if they exist.

The growing popularity of gasoline fuel injection is primarily due to the development of low cost/low pressure (typically 70-250 kPa) throttle body injection systems. Experimental propane fuel injection systems have been tried with some success but there are significant technical and economic problems with designing a system for production. To maintain the fuel in a liquid phase at a temperature of 90°C (not uncommon for underhood temperatures) would require the fuel system to operate at 3700 kPa. (The metering mechanism required for a two-phase system would be too complex for consideration at this time.) If temperatures rose above 97°C, the critical temperature of the liquid, then a liquid phase would not form and the injectors would have to inject gaseous propane at pressures of 4200 kPa and greater.

The primary advantage offered by LPG fuel injection is increased power output. Liquid propane injected into the incoming air stream would vaporize by absorbing heat from the air. This would drop the temperature of the charge by approximately 27°C (for dry air) increasing the available charge density. Theoretically, power output could be improved by approximately 10% over conventional propane carburetion. Some slight fuel economy improvements would also be possible as a result of the advanced electronic controls, but the benefit would be no greater than offered by the electronic open loop system and the cost would be much higher.

4.3.5 Pressure Regulator/Vaporizer

The pressure regulator and vaporizer are usually combined into a single unit sometimes called the converter and they are considered as part of the carburetion system. Most pressure regulators are similar in principle and use diaphragms and lever valves to reduce the tank pressure in two or sometimes three stages to a pressure which is usually slightly below atmospheric pressure.

The vaporizer is a heat exchanger using heat from the engine coolant to vaporize the liquid propane, which requires 218 kJ per litre at its boiling point of -42°C. It is very important, therefore, to connect the vaporizer to the engine cooling system in such a way that an adequate flow of water is insured at all times. Many installations, particularly those in the aftermarket, make use of the car heater circuit and connect the vaporizer either in series

or in parallel with the heater. This does not usually cause any problem during warm weather, but during cold temperature operation either the heater or vaporizer may get inadequate flow when connected in parallel. When connected in series, the added restriction in the circuit will reduce the flow of coolant, impairing the performance of both the vaporizer and car heater. For this reason, the vaporizer and car heater should each have their own separate circuit with the coolant lines sized to provide adequate flow under all conditions.

The most critical period is during start-up of a cold engine. At this time there may be insufficient heat transfer to vaporize the liquid propane and the engine may die-out due to a lack of vaporized fuel. Subsequent vaporization of the liquid fuel in the vaporizer may force propane into the engine, flooding it and making it difficult to restart.

It is easy to see why a vaporizer with sufficient capacity for operation in warm climates may prove to be inadequate during severe Canadian winter conditions.

Although automotive propane is one of the purest high volume products produced and marketed by the gas and petroleum industries, problems often occur with oily or tarry deposits in the converter. An investigation into the propane produced from eleven different sources showed that all were well within specification and contained no contaminating materials (Ref. 24). It is generally conceded that most contaminants are picked up between the point of production and the time it reaches the vaporizer. Most contamination probably stems from:

- lubricating oil used in the propane pumps and compressors in the distribution system.

- dust or dirt picked up from couplings or hoses that are carelessly handled.

- plasticizers used in the rubber fuel lines which are leached out by the propane.

Some of these contaminants are passed through the vaporizer and burned in the engine, but a significant portion are deposited in the vaporizer when the liquid propane evaporates. Over a period of a year and a vehicle metrage of 15 000 km, a total volume of 2000-3000 litres would be evaporated and even a small amount of contaminant would gradually build up.

There is also some suspicion that olefins, unsaturated hydrocarbons in the propane, may polymerize when exposed to high temperatures in the vaporizer and form gummy deposits. Propylene is one of these and can be present in concen-

trations as high as 5%. There may therefore be some merit in controlling the upper temperature limit of the vaporizer. The Australian industry is conducting laboratory tests with different concentrations of propylene to investigate the role it plays in gum formation. The work is being carried out in a joint effort by the automotive industry, equipment manufacturers and the oil and gas industry (Ref. 25). The results of this investigation may provide some answers to the problem.

On the assumption that the problem will likely continue, whatever the cause, one conversion equipment manufacturer , Vialle, has developed a system which purges the vaporizer by means of suction every time the engine is turned off. The vacuum obtained from the intake manifold is stored in a vacuum reservoir. When the engine is turned off, the suction is admitted to the converter and sludge drawn into a collector bottle which can be emptied at appropriate intervals. The arrangement of this equipment is shown in Figure 19.

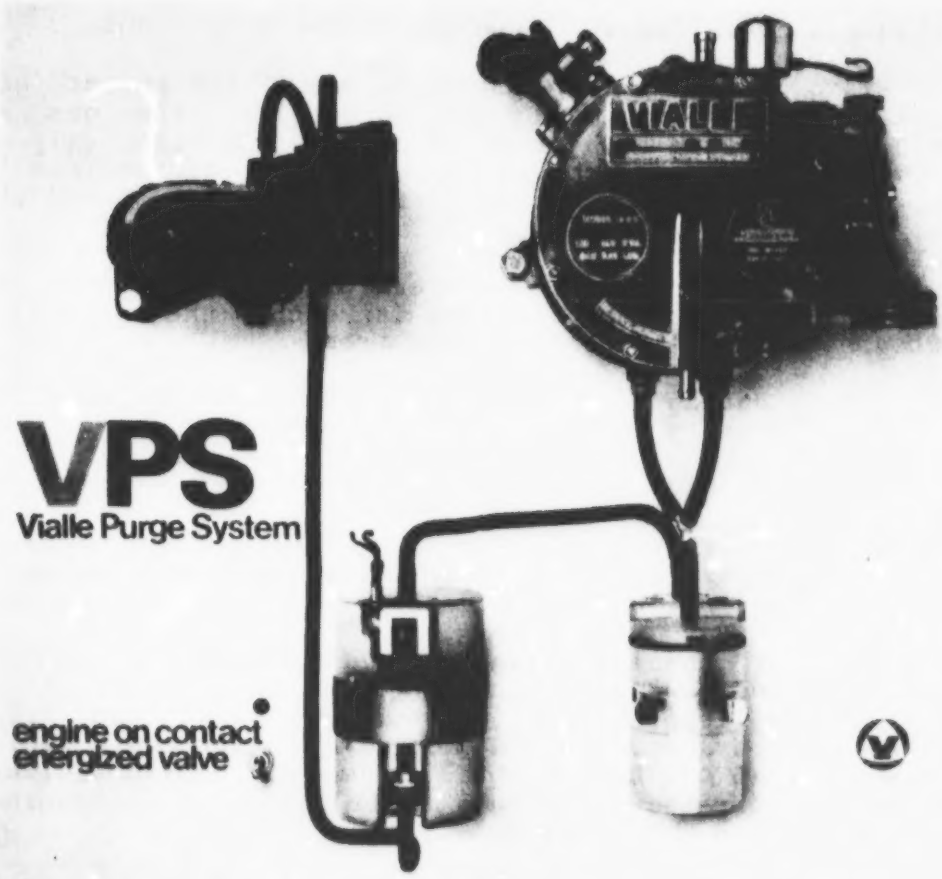


Figure 19 - Vialle Vaporizer Purging System

4.3.6 Conclusions and Recommendations

(1) In a multi-cylinder engine good fuel-air distribution is a fundamental requirement irrespective of the fuel used if expected power output, fuel consumption, and overall performance is to be achieved.

(2) Gaseous fuel has more potential for achieving good fuel-air distribution than liquid fuel but good distribution with gaseous fuels will not be realized unless satisfactory mixing of fuel and air is assured.

(3) Evaluation and optimization of fuel-air distribution should be a basic requirement for every engine system designed for, or converted to, propane use.

(4) When designing engine systems for propane, positive actions to insulate the intake manifold from exhaust heat will improve volumetric efficiency.

(5) Single cylinder investigations demonstrate that propane fuel-air equivalence ratios are leaner than gasoline for both maximum power and minimum fuel consumption.

(6) Multi-cylinder engines using propane will probably require leaner fuel-air equivalence ratios than gasoline if the fuel-air distribution is optimized.

(7) When good mixture distribution is achieved with a propane engine, the fuel-air equivalence ratio, Fr, is less than with gasoline for maximum power. Mixtures richer than necessary for maximum power should be avoided with propane as the drop in power is much sharper than when gasoline is used.

(8) Although closed loop feedback control systems may have the potential to improve fuel economy and/or power output over currently available off-the-shelf carburetion systems, they do not provide optimum fuel control. Both advanced mechanical control systems and electronic open loop control provide the most potential to provide "ideal" fuel-air ratio tailored to individual engine designs.

(9) Liquid propane fuel injection is not expected to be a viable alternative to present systems in the short term.

(10) Heat transfer capability of a propane vaporizer is extremely important and is probably the most important cause of operating problems during start and warmup at ambient temperatures below $-10^{o}C$.

(11) The method by which the vaporizer is connected into the engine cooling system is very important to the performance of the vaporizer and other equipment such as the car heater.

(12) The sludging tendency of propane in a vaporizer may be influenced by the temperature of the vaporizer. This should be evaluated to determine if the vaporizer temperature needs to be controlled at some upper limit.

4.4 Ignition

4.4.1 General

Spark timing is interrelated with almost every other variable associated with the S.I. engine. It influences, or is influenced by, the combustion property of the fuel used, anti-knock property of the fuel, compression ratio, engine speed and load, combustion chamber shape, and intake air temperature. It follows, therefore, that every engine must have its spark timing schedule specifically tailored to that engine, a procedure which requires engine dynamometer test work followed by confirmatory vehicle road tests to insure satisfactory vehicle performance and driveability. This review will concentrate on the differences that result from using propane instead of gasoline.

4.4.2 Spark Advance For Power and Fuel Economy

As discussed in section 2, the combustion properties of propane and gasoline are significantly different, particularly with respect to ignition delay and combustion periods. This information helps us to understand why spark timing for propane and gasoline will usually differ, but it does not permit us to predict what the ideal spark timing should be for either fuel in a particular engine. To determine the optimum timing for an engine running on propane it is necessary to run engine dynamometer tests. Figure 20 shows, for example, the propane and gasoline timing curves of minimum spark advance for best torque (MBT) for a Chrysler 8-cylinder engine. For this engine MBT timing for propane is 2-3 degrees retarded from MBT timing for gasoline over the full speed range. Other engines may show MBT timing for propane to be more advanced than gasoline or to be retarded from gasoline in one speed range and more advanced in another speed range (Ref. 5,13,21,26). It is therefore easy to see that the standard aftermarket rule-of-thumb of advancing the spark timing 10-20% at low speeds and retarding the timing 10-20% at high speeds (Figure 21) may in many cases do more harm than good.

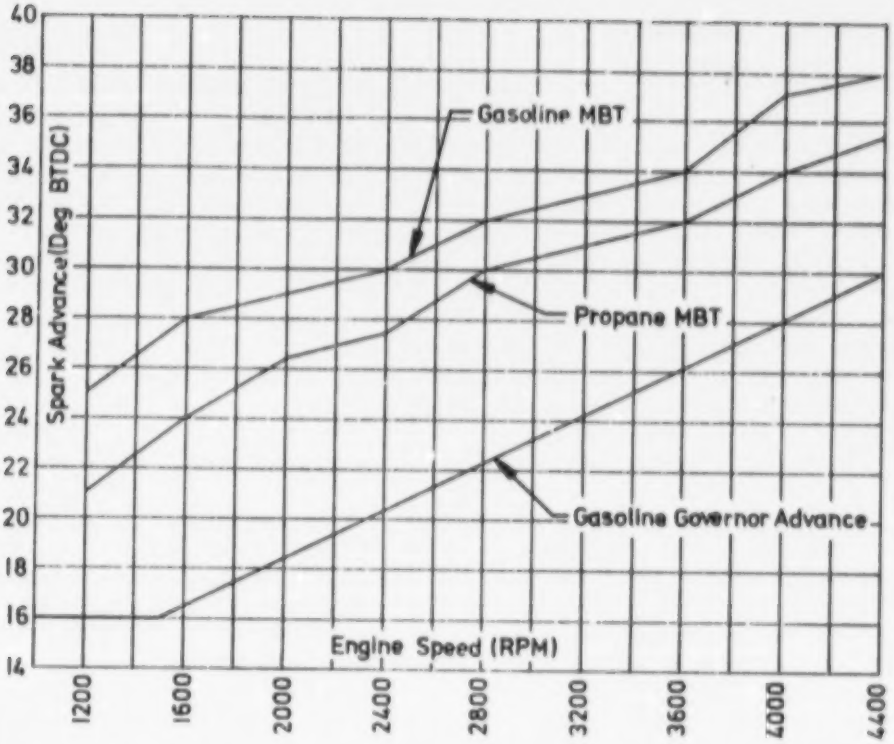


Figure 20 MBT And Governor Spark Advance Curves For Chrysler 8—Cylinder Engine

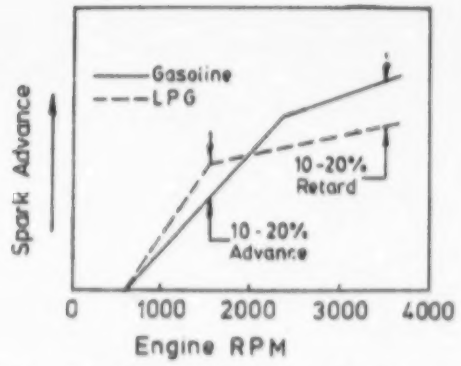


Figure 21 Typical Distributor Advance Curves Used In Some Aftermarket Conversions

The gasoline governor curve used in production on Chrysler's Canadian gasoline cars is also shown in Figure 20. Note that the curve is retarded 8 to 10 degrees from the MBT gasoline curve. This is commonly done for several reasons: to lower exhaust emissions, to avoid spark knock that would occur at MBT timing (see following section on knock limited spark advance) and to provide a margin of safety, particularly at high speeds, for engine-to-engine variations which could result in detonation or preignition leading to engine damage. Note that, at the same compression ratio, the need for this margin of safety may not exist with propane because of its high octane rating. In the case of this engine running on propane it is possible to set the governor curve at MBT timing and hence take advantage of propane's higher octane rating, since during dynamometer testing no spark knock was observed, even when the spark was advanced several degrees past MBT timing. Of course, if the compression ratio was increased on the propane engine, it may be necessary to retard the timing several degrees from MBT advance for the same reasons as done on gasoline.

During part throttle engine operation a vacuum advance component is added to the governor spark advance to give the correct spark advance for optimum fuel efficiency and driveability. The vacuum advance curve is generally developed based on engine and chassis dynamometer tests as well as on-road driveability tests, and will vary substantially from engine to engine based on the F/A ratio calibration, the use of exhaust gas recirculation (EGR), and several other factors (intended application, exhaust back pressure, etc.). The optimum vacuum advance curve for propane will almost certainly be different from the optimum curve for the equivalent gasoline-fueled engine and will have to be determined based on dynamometer and on-road tests.

4.4.3 Knock Limited Spark Advance

MBT spark advance is sometimes not achievable in a given engine because of engine knock or detonation. The main factors limiting the spark advance before the onset of engine knock are compression ratio, combustion chamber design, the octane rating of the fuel used, and the temperature of the intake fuel-air mixture, the latter being very important when using gaseous fuels. For a given engine, the spark timing curve should be designed so as to avoid detonation with the lowest octane fuel likely to be used. Figure 22 (Ref. 5) shows the MBT timing and knock limited spark advance (KLSA) for an engine using 100 octane gasoline and propane. Using gasoline below 2600 RPM, the distributor spark curve will be limited by KLSA and be as much as 7 degrees retarded from MBT timing. Above 2600 RPM, there is a safety margin between MBT and KLSA which permits ignition timing for best power output. The 9.9:1 compres-

sion ratio used with this engine would not be possible with lower octane regular grade gasoline.

The same engine using an LPG blend containing 10% propylene had a margin of safety between MBT and KLSA at both high and low speeds but borderline knock was experienced around 2400 RPM with MBT spark timing. Automotive grade propane with a maximum content of 5% propylene and a higher motor octane value would probably be free of knock at all speeds with MBT timing on this engine.

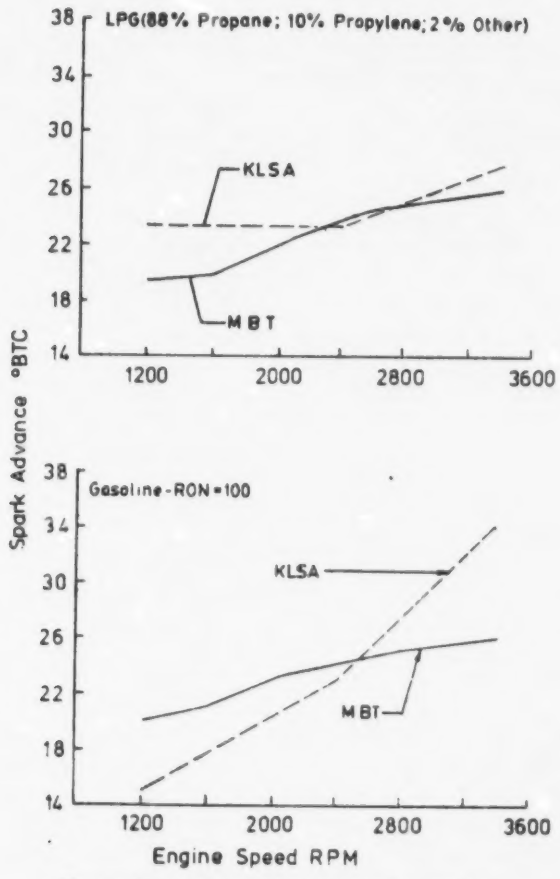


Figure 22 KLSA And MBT Spark Timing —413 CID Engine; 9.9:1 C.R. (Ref. 5)

The shape of the KLSA curves for propane and gasoline should be noted. KLSA for gasoline increases sharply with speed, whereas KLSA for propane has less increase and even shows a decrease under some conditions. This same characteristic of KLSA for propane has been pointed out by other investigators (Refs. 9,10,13,27). Figure 23 shows

the findings of Kuivanen et al (Ref. 13). Note the higher compression ratio possible with propane because of its higher octane rating. When this engine is fueled with propane, the spark advance curve can be set at MBT with several degrees safety margin across the full speed range protecting it from engine knock. On the other hand, with gasoline, spark advance will be knock limited below 1400 RPM and above that the margin between MBT and KLSA is very small.

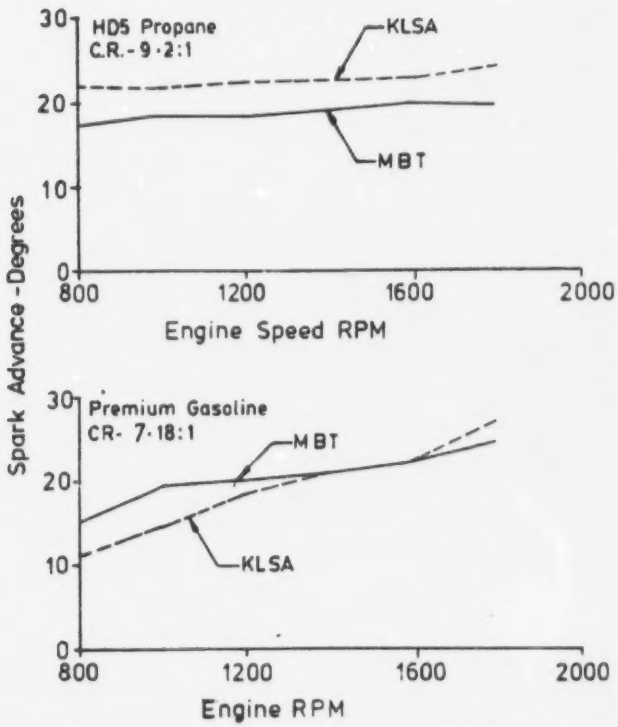


Figure 23 Spark Advance Characteristics
—425 CID Engine (Ref.13)

The KLSA with propane is also influenced by carburetor intake temperature and by engine coolant temperature. Armor et al (Ref. 27) determined the effect on a number of engines and Figure 24 illustrates KLSA of an engine for three intake temperatures and two engine coolant temperatures.

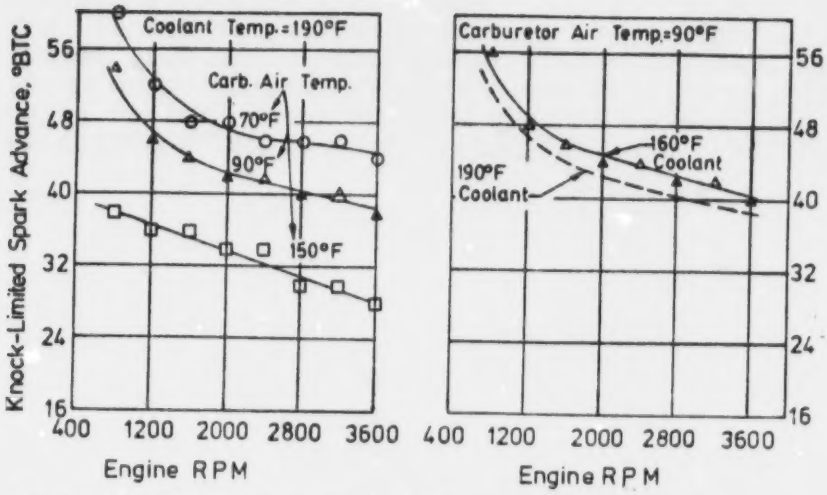


Figure 24 Effect Of Carburetor Air And Engine Coolant Temperatures On The Knock-Limited Spark Advance With Propane (Ref.27)

It is clear that if intake air or mixture temperature is not controlled to reasonable limits, satisfactory knock-free performance will not likely be experienced, particularly at higher compression ratios. The influence of water jacket temperature, although in the same direction as inlet temperatures, is much less pronounced. This effect is apparently the reason why colder engine thermostats are sometimes substituted when vehicles are converted from gasoline to propane. The small improvement in KLSA is outweighed, however, by the problems arising from using a colder coolant temperature, particularly heater and defroster performance, and the practice should be avoided.

4.4.4 Spark Plugs

The specification of the correct spark plug in an engine is critical because it controls the delicate balance between plug-induced preignition and plug fouling. Figure 25 shows the general relationship between load and temperature of the spark plug nose (Ref. 28). The plug must operate hot enough to burn off any carbon deposits which might cause fouling but not so hot as to be a source of preignition. For best service, the plug should operate between 400°C and 800°C (752°F and 1472°F) during cruise conditions. This also protects against erosion of the electrodes by oxidation at high temperatures. The choice of heat range for spark plugs will be influenced by the type of service. For taxi cab service where there is a lot of

idling, a hotter plug may be required than for the same vehicle used as a police highway patrol car. In the former case, a hotter plug protects against fouling; in the latter case, a colder plug protects against preignition.

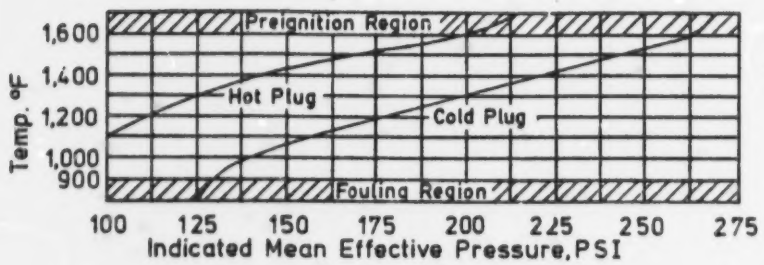


Figure 25 Effect Of Load On Temperature Of Spark Plug Core Nose (Ref. 28)

Since many of the changes made to an engine to make it compatible with propane can affect spark plug nose temperatures, a different spark plug heat range is sometimes recommended (Refs. 9,22,26). Fig 26 (Ref. 9) illustrates a typical difference found. In this particular case, several engine parameters were changed to compensate for the fuel differences. The compression ratio was increased, the spark timing set to MBT for propane (gasoline engines are rarely set to MBT), and the fuel/air ratio adjusted to optimize part throttle fuel consumption and WOT power. The spark plugs required were one heat range colder than required with gasoline.

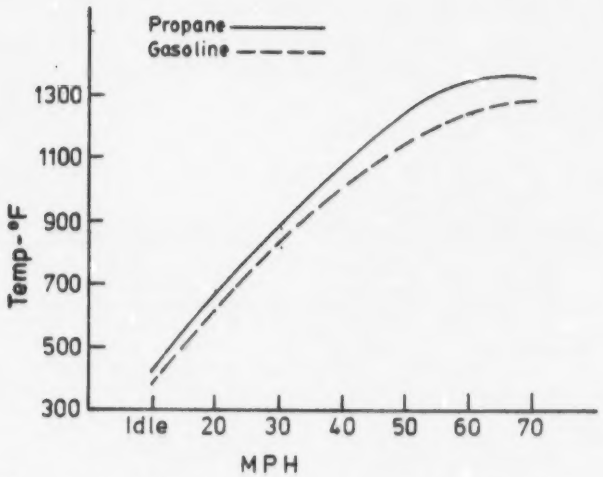


Figure 26 361 CID Engine Spark Plug Temperature For Propane And Gasoline (Ref. 9)

It is common field practice to use colder spark plugs with reduced gaps to compensate for the higher voltage requirement. This practice rarely causes any harm because plug fouling is rarely a problem with propane. Fig 27 shows the effect of spark plug tip temperature and electrode gap on voltage requirement. (Ref. 9)

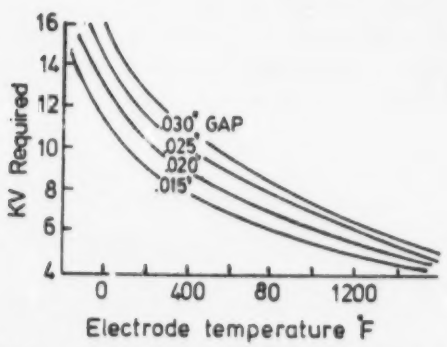


Figure 27 Effect Of Electrode Temperature And Spark Plug Gap On Voltage Required (Ref. 9)

With old type breaker point ignition systems, reduced gaps were often required to prevent ignition failure. Modern electronic ignition systems are more reliable and

usually have higher reserve voltage capabilities. For this reason, narrower gaps are rarely required, and should be avoided unless breakdown occurs. (Cold start and engine idle require wider gaps than are necessary at higher speeds. Very lean mixtures also favour wide gaps).

If major changes are made when optimizing an engine for propane, the spark plug temperatures could change substantially and it will be necessary to start from scratch to determine heat range and plug gap requirements.

4.4.5 Electronic Spark Advance

The basic spark timing requirements for an S.I. engine are:

- a retarded spark for easier starting
- increasing spark advance with engine speed at full load for maximum power
- additional spark advance at part load for minimum fuel consumption.

The conventional ignition systems have met these requirements by a basic timing setting for start and idle, centrifugal weights in the distributor for increased advance as engine speed increases, and by a manifold vacuum-operated control to provide additional advance at part load conditions. This system has been developed to a high state of efficiency but it does not have the flexibility to provide all the spark advance requirements over the full range of engine operation to give optimum performance and fuel economy.

The evolution of electronic microprocessors and sensing units has permitted the development of spark advance systems which can assimilate and process a large number of inputs to give the optimum spark advance at any instant. In addition to engine speed and manifold vacuum used by the conventional systems, electronic spark advance may also evaluate other inputs such as:

- throttle position
- coolant temperature
- intake charge temperature
- knock sensor information

The benefits of electronic spark advance are applicable to both gasoline and propane-powered vehicles and can provide:

- improved driveability

- improved fuel economy

- lower exhaust emissions

Each fuel will have its own engine spark schedule for a vehicle, but electronic spark advance permits a manufacturer to incorporate both schedules into one unit for a dual-fuel system. The cost of a dual-fuel electronic spark advance unit with two spark schedules is not expected to be substantially more expensive than the cost of one with a single spark schedule. There would, however, be an initial cost to program the electronic spark advance unit for its dual function.

4.4.6 Conclusions and Recommendations

(1) Spark advance requirements for an engine are specific to that engine and have to be determined by standard dynamometer test methods as well as on-road evaluations.

(2) With any given engine, the spark timing requirements for propane and for gasoline will usually be different but the degree of difference is unpredictable.

(3) Arbitrary changes to spark timing based on "rule-of-thumb" when converting from gasoline to propane may do more harm than good.

(4) Because of their relative anti-knock properties, an engine is less likely to be knock limited when using propane than when using gasoline. Nevertheless propane is sensitive to high intake mixture temperatures and every effort should be taken to keep the intake manifold temperatures as cool as possible in order to avoid detonation and/or preignition and to maximize power output.

(5) The practice of substituting colder engine thermostats than specified by the engine manufacturer probably does more harm than good.

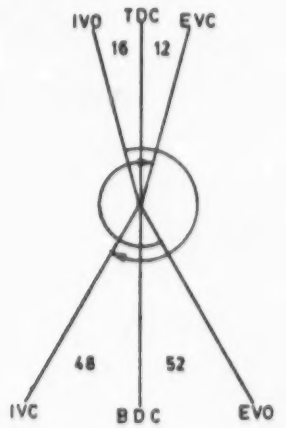
(6) Spark plug gaps and heat ranges should be determined by the vehicle manufacturer when designing for propane in the same way as these parameters are determined for gasoline.

(7) With modern electronic spark advance systems it is practical to provide dual spark advance curves for an engine, one optimized for gasoline, the other for propane.

4.5 Valve Timing and Intake Manifolds

4.5.1 Valve Timing

In a spark ignition engine, valve timing has a major influence on engine performance, fuel consumption and driveability. Theoretically, valves can open and close at each end of the intake and exhaust strokes, but at high speeds, early opening and late closing is necessary because of the inertia of the working fluids. Figure 28 (Ref. 29) illustrates the valve timing points for a modern high speed automotive engine.



Valve Timing Diagram

Figure 28 Typical Valve Timing Diagram For A Modern, High Speed, Four Cylinder Engine (Ref. 29)

When determining the timing of valve events, the major concerns are idle and wide open throttle operation. Valve overlap affects combustion adversely at idle because excess amounts of exhaust gas mix with the incoming fuel-air charge while at high speed, volumetric efficiency is influenced primarily by valve overlap and the timing of inlet valve closing. During part throttle operation, the volumetric efficiency and engine output are deliberately controlled by the carburetor throttle valve and valve timing is not so critical. Optimization of valve events, then, is fundamentally seen as a task to minimize valve overlap for idle while maximizing high speed WOT performance by retaining enough overlap to keep pumping losses within tolerable limits.

Figure 29 (Ref. 29) illustrates the effect of overlap

on the P-V diagram of an engine at idle. The right hand diagram results from a valve overlap of 16 compared to 28 in the left hand diagram. Reducing the overlap by a later opening of the inlet valve gives a higher pressure rise indicative of faster combustion.

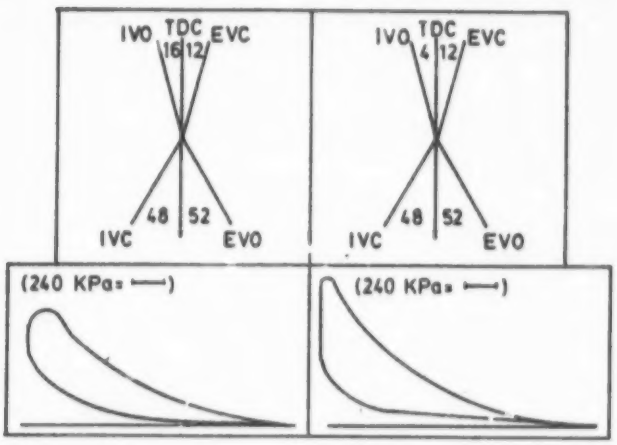


Figure 29 Idle PV Diagrams Showing The Effect Of Valve Overlap In A Chrysler 2.2L Engine-Spark Timing=25° BTDC (Ref.29)

It is possible, therefore, within the limits of preserving WOT performance, to improve idle quality as well as improve fuel consumption at idle through valve timing modifications.

Timing of inlet valve close (IVC) is also a compromise between high and low speed performance. IVC always occurs after the end of the intake stroke and at high speeds this helps to fill the cylinder with the incoming fuel-air charge. At low speeds, late IVC causes part of the fresh charge to be pushed back into the intake manifold reducing the volumetric efficiency. It is, therefore, possible to modify the shape of the torque curve by adjusting IVC to favour high or low speed performance.

The influence of valve timing does not appear to be affected by the fuel used. Tests by Ricardo Engineering wherein valve timing was modified had exactly the same impact on propane and gasoline-powered versions of the same engine (Ref. 25). Nevertheless, there may be opportunities to use valve timing modifications in a beneficial way when converting from gasoline to propane. If, by increasing compression ratio or other modifications, the power output

with propane is increased beyond the power available with gasoline, changes to IVC and valve overlap could be made to favour idle and low speed performance while still retaining WOT performance equal to gasoline. Since propane typically provides better low speed air-fuel mixture distribution than gasoline, improving idle performance even more by reduced overlap holds good potential for reduced idle speeds and therefore reduced idle fuel consumption.

4.5.2 Intake Manifolds

In a carbureted engine, as opposed to a multi-point fuel injected engine, the intake manifold is designed to distribute fuel and air to each cylinder as uniformly as possible so that each cylinder receives the same amount of fuel-air charge and so that the fuel-air ratio at each cylinder is the same.

Since almost all automotive spark ignition engines are designed for gasoline, the intake manifold is also designed to accommodate that fuel. The carburetor meters the liquid gasoline into the air stream entering the manifold where it is atomized, partially vaporized, and mixed with the air. One of the main aims in the design of the manifold is to discourage large droplets of liquid gasoline which tend to fall out of the stream. To prevent this, turbulence is often encouraged by raising the intake velocity through reduced cross-sections, but this in turn increases intake restriction and lowers volumetric efficiency. The development of a manifold is, therefore, very much of a compromise when designing for gasoline.

The cylinders receive a mixture of air, vaporized fuel and atomized droplets of liquid fuel. In order to achieve satisfactory distribution with gasoline, some heat must be added to the manifold in order to partially vaporize the incoming liquid fuel. The more the fuel is vaporized, however, the more adverse is the effect on volumetric efficiency because the volume of vapour is much larger than the volume of liquid and displaces air, thereby lowering the total mass of charge to the cylinder. The challenge is to add only sufficient heat to get good distribution without significantly affecting volumetric efficiency. Usually about 60% vaporization of the gasoline in the manifold at wide open throttle provides the best value for good distribution and maximum power (Ref. 27).

Propane, being metered as a gas, requires no heat in the manifold and indeed heating the intake mixture will decrease its density and lower the volumetric efficiency (see section 4.3). Heating the intake charge will also lower the KLSA as discussed in section 4.4.3. For these reasons, the intake manifold should never be heated when propane is used as the fuel. Most dual-fuel systems,

however, continue to use a heat crossover or hot spot to maintain good performance with gasoline, but this is only done at the expense of diminished power and performance with propane.

Despite the fact that propane is introduced into the air as a gas, good mixing and distribution are not automatically achieved. Some turbulence is essential and the manifold must be sized so that each cylinder receives the same volume of mixture. It is probable that merely blocking off the heat crossover on a gasoline engine is insufficient to optimize the intake manifold for propane. It is more than likely that modifications to the intake manifold geometry can improve mixing while at the same time lowering the intake restriction and thereby improving volumetric efficiency and power output.

4.5.3 Conclusions and Recommendations

(1) The influence of valve timing does not appear to be affected by the fuel used.

(2) If the compression ratio of an engine is raised when modifying it for use with propane, the power output will probably be higher than when gasoline is used at the standard ratio. In that event, a change in valve timing to modify the torque curve to give better idle and part throttle performance may be desirable.

(3) Intake manifolds designed for gasoline are unlikely to give optimum performance with propane. Fuel-air mixing and distribution can probably be improved by a change in manifold design that goes beyond merely blocking off the heat riser or hot spot.

4.6 Engine Durability

4.6.1 General

The use of propane in a spark ignition engine causes few unusual problems affecting durability of the engine. The only one of any significance is valve seat wear, predominantly exhaust valve seats, but instances of intake seat wear and recession have been observed. With dedicated propane engines, piston compression rings do not wear in or seat themselves as quickly as when gasoline is used and as a result somewhat higher oil consumption is sometimes experienced. The only other concern for durability is if the compression ratio is increased when using propane. In most cases there is sufficient structural integrity in the engine to permit some increase in the compression ratio with only minimal changes to the engine, but this should be checked to ensure that no overloading takes place.

Practical compression ratio increases obtainable with propane will likely involve only limited modifications to the engine such as heavier duty bearings or gaskets.

4.6.2 Valve Seat Recession

The valve seat recession problem is a complex one and the mechanisms leading to it are not completely understood. Recession of the valve seat in a cast iron head is usually accompanied by the presence of a red iron oxide deposit on the underside of the exhaust valve which has its seating surface marked with irregular wart-like craters. It is speculated that local welding transfers particles of the iron seat to the valve and these are then pounded into the valve face forming craters with raised edges. The raised edges of the craters reduce the area of contact increasing unit pressure and wear away the seat when there is relative motion of the valve and seat. The iron transferred to the valve is exposed to much higher temperatures than when part of the valve seat and oxidizes giving rise to the typical reddish deposit associated with rapid seat recession (Ref. 30).

The problem does not arise when leaded gasoline is used since the presence of tetra-ethyl lead (TEL) (used as an octane improver) prevents wear by acting as a lubricant between the valve and its seat. When unleaded gasoline was introduced in the early 1970's in response to the need for exhaust emission catalytic converters, the automotive manufacturers found it necessary to use either hard alloy inserts or, in the case of cast iron heads, to induction harden the exhaust seats in order to obtain satisfactory durability.

Because propane enters the cylinder as a dry gas and has virtually no lubricating properties and also contains no additives such as TEL, it has always been found necessary in the past to use hard alloy exhaust seats for propane-fueled engines. It was anticipated that engines designed for use with unleaded gasoline would have no problem when propane was used as an alternative fuel but this has not proved to be the case. In almost all cases high rates of valve seat recession will occur when propane is used. An increase in the rate of seat wear by a factor of 5 is typical, and wear rates as high as 10 times that for gasoline are not uncommon. The worst examples of seat wear are associated with high speed, high load operation (both for gasoline and propane) but other factors may be of considerable importance. Sometimes all valve seats will show heavy wear, while at other times only certain cylinders will have high wear. Giles and Updike (Ref. 31) found speed rather than temperature to have the greatest influence where unleaded gasoline is used and this may also be true with propane.

The use of nickel or cobalt-based high-alloy valve seat inserts and hard-faced valves has for many years been specified as the best valve and seat packages for propane-fueled industrial engines. However, there is reason to believe that even these combinations do not provide the low level of wear experienced with present gasoline engines operating on unleaded fuel. Installation of high-alloy valve seat inserts and hard-faced valves also adds significantly to the cost of an engine -- both in piece cost penalty, and "off-line" seat installation cost. It is, therefore, highly desirable to investigate other means of reducing valve seat wear. The use of flatter valve seat angles (20 or 30 vs 45) has been shown to reduce recession in some cases and increased seat width may have merit in providing increased heat transfer surface (Ref. 31). The effect of engine oils and engine oil additives is a subject worth investigating. While most propane engine manufacturers specify ashless and low ash oils, Waukesha, who have been building natural gas and propane engines for decades, specify high barium and calcium additives and point out that valve seat wear is substantially reduced when oils having a high ash content are used (Ref. 32).

The relationship between valve seat recession and the presence of TEL in gasoline is very marked and although results of tests are highly variable, seat wear can increase by a factor of 20 when unleaded gasoline is substituted for leaded fuel (Ref. 30). On the other hand, why the use of propane causes more seat recession than unleaded gasoline is not fully understood. It may be due to products of combustion not found with the relatively pure propane or because so-called unleaded gasoline is permitted to have a lead content of 13 mg/L. It would be interesting to determine the influence of a similar amount of lead in propane. In addition, other fuel additives could be tested for their effect on valve seat wear.

In light duty engines, exhaust valves are usually designed to be free to rotate when lifted off the valve seat, the rotational force being imparted by the engine vibration, the flow of gases past the valves, and valve spring windup. The amount of rotation is uncontrolled and at high engine speeds valve rotation usually increases exponentially. This can lead to high recession rates caused by the scrubbing action when the valve seats. For heavy duty gasoline engines, it has been common practice to specify positive valve rotators which impart a controlled amount of rotation each time the valve is lifted off its seat, thereby preventing rotational scrubbing of the seat as the valve closes. This provides the most even temperature distribution for the valve and minimizes the formation of hot spots on the valve head. It also crushes and cleans away any deposits that may form on the valve face and provides even valve tip and stem wear.

A few designers specify non-rotating valves for propane-fueled engines to minimize valve seat wear. To minimize rotation, the valve stem is gripped tightly by valve spring retainer locks. This practice loses the benefits of rotation and may result in increased chances of valve burning due to deposit buildup or the formation of hot-spots on the valve head. It should be noted that at high engine speeds (greater than 4000 RPM) valve shuffling on the seat will likely occur with any of the above types of rotation and seat wear will be substantially increased.

In summary, positive valve rotators appear to provide the best set of conditions for a propane-fueled engine with "minimum" rotation being the second choice.

Dual-fuel leaded gasoline/propane engines may experience much less valve seat wear. The lubricating properties of the lead additives have a carry-over effect and if leaded gasoline is used from time to time, the lubricating deposit between valve and seat is renewed. Despite this, in Europe where almost all vehicles using propane are dual-fuel, hard-faced exhaust valves and cobalt-based exhaust valve seats are normally specified.

4.6.3 Piston Rings

Piston rings, while much less of a problem than valve seat wear, are still worthy of special consideration. For heavy-duty gasoline engines, compression rings are sometimes chrome-plated to prevent ring wear and bore scuffing. When the engine is cold, unvaporized liquid fuel enters the cylinder, diluting the oil on the cylinder walls and permitting increased metal-to-metal contact. Chrome-plating the ring prevents excess ring wear and bore scuffing during this period. When propane is used, however, it is completely gaseous and there is no tendency to remove the oil from the cylinder wall. There is a common belief that this results in chrome-plated compression rings not breaking in properly on propane and that the engine designer should specify a softer tin-plated or molybdenum-filled top ring. This is done by most of the industrial propane engine manufacturers. However, the belief is not unanimous among automotive engine designers as to whether this practice is necessary in a modern automobile engine. An investigation is needed to evaluate the various piston ring designs for application in automotive propane engines.

Vehicles that are originally built for gasoline and then converted to propane have no problem with chrome rings as the break-in process is for the most part complete within several hundred kilometres of running on gasoline. European manufacturers do not specify special ring packages for their dual-fuel vehicles and do not report any ring break-in problems.

4.6.4 Conclusions and Recommendations

(1) Except for valve seat wear or recession, a propane-fueled engine poses no significant durability problems beyond those experienced with the same engine using gasoline.

(2) If the compression ratio is increased when using propane, the manufacturer must assure himself that no additional durability problems result on that account.

(3) Exhaust valves and valve seats designed for use with unleaded fuel are unlikely to be adequate for use with propane.

(4) The use of hard-faced exhaust valves and high-alloy valve seat inserts will likely reduce the rate of exhaust seat recession when propane fuel is used, but wear rates will likely remain significantly higher than in the equivalent gasoline engine.

(5) A major effort is required to develop economical valve and seat insert materials and/or fuel and oil additives that will provide comparable valve and seat wear to what is experienced on unleaded gasoline fueled engines.

(6) A development program is needed to evaluate the compatability of various ring designs with propane-fueled engines.

4.7 Engine Lubrication

4.7.1 General

As has been pointed out elsewhere in this report, there is a great deal of interdependency between all of the variables of an internal combustion engine. Spark advance, fuel-air ratio, compression ratio, and the fuel itself all affect one another. This is also true for engine lubricating oils. Lubricating oils have evolved hand in hand with the spark ignition engines; as engines became more efficient and outputs increased, so have engine oils and additives become more sophisticated and complex. Most manufacturers of gasoline-fueled vehicles specify API-designation SF engine oil, the latest in a series of increasingly demanding test sequences.

Fuel and engine oil have a strong influence on each other; gasoline finds its way into the oil and engine oil and its additives find their way into the combustion chamber. When propane is used instead of gasoline, we find no fuel getting into the oil to react with it or dilute it.

On the other hand, engine oil can still get into the combustion chamber, usually by way of the intake valve guide. When this happens with gasoline, liquid fuel entering the cylinder tends to remove the oil from the stem and under-head area of the intake valve. With propane, there is a tendency for tar-like materials from the oil to build up on the intake valve. These normally cause no problem but a situation can be visualized where with some oils, the build up on the intake valve could restrict flow of the inlet charge and reduce maximum performance or hold the valve off the seat and cause valve burning. This is a characteristic of engine oil performance in propane engines that needs to be investigated.

Particularly during cold starts, liquid gasoline finds its way into the cylinder and past the piston rings into the engine oil. Positive crankcase ventilation helps to evaporate the gasoline but, in the winter especially, a significant quantity of gasoline is present in the engine oil. Sooty smoke generated by incomplete combustion of gasoline during cold starts also finds its way into the crankcase giving used engine oil its typical dirty appearance. Along with gasoline and water vapour, the carbon particles also tend to form a tar-like sludge. The particles are removed by the oil filter or kept in suspension by the detergent additives in the oil which remains serviceable even with a dirty appearance. In short, engine oils have been developed to suit the conditions of operation with gasoline.

Propane causes no crankcase dilution and being a relatively clean-burning fuel with no need for rich mixtures during warmup, there is much less sooty carbon material getting into the oil, which may tend to remain brighter and cleaner than experienced with gasoline thus giving the impression that the oil has suffered no deterioration and remains unchanged from new oil. This in turn gives impetus to the claim that when using propane, engine oil drain periods can be extended. Unfortunately, used engine oils cannot be evaluated visually; a laboratory analysis is required. Oils tend to thicken from oxidation and nitration and there have been reported cases of oil in propane engines that looks bright and clean but which with a drop in temperature will become very thick, sometimes to the point of turning into a gel. For this reason we must approach increased oil drain periods for propane engines very cautiously. There may be a case for increased engine oil life when using propane but it needs to be proved by controlled tests rather than assumed because of the appearance of the oil. Limited testing conducted to date by Chrysler Canada has shown that oil drain periods for propane should be the same as for gasoline.

Before considering extended life for engine oil in propane engines, the first question to be considered should

be whether present widely available engine oils specified for use with gasoline engines are satisfactory when used with propane or whether specially compounded oils are required. The ideal answer to that question would be that the same oils could be used for both gasoline and propane, simplifying availability and probably ensuring a lower cost. We cannot assume the answer; even if in the past there was a particular reason for requiring a special oil for propane, the new SF oils may be quite satisfactory.

V.E. Broman (Ref. 33) recommends a stable high viscosity index (VI) oil with a rust inhibitor, an ashless dispersant, a pour depressant, an anti-oxident and an anti-foam agent. Most propane engine manufacturers recommend ashless or low ash oils but Waukesha, based on research into exhaust seat wear, recommends the use of oil with high ash producing barium and calcium additives (Ref. 32).

In summary, recommendations for extended oil drain periods should be ignored unless clearly demonstrated in a test program with specific oils. More detailed research is necessary to determine whether SF oils are satisfactory for propane engines and whether engine oil additives can help reduce exhaust valve seat wear.

4.7.2 Conclusions and Recommendations

(1) There is no reason to conclude that engine oils specified for modern high speed light duty engines are not satisfactory for propane.

(2) There is no reason to conclude that engine oil drain periods can be extended when using propane. The appearance of used oil can be deceiving.

(3) It may be possible to use an engine oil additive to reduce exhaust valve seat wear.

5. FUEL STORAGE AND HANDLING SYSTEMS

5.1 Overview

Beyond putting fuel and sometimes oil in his car, the average owner is not very familiar with or concerned about the workings of his vehicle; he expects it to operate faultlessly winter and summer. His expectations may not be entirely reasonable or indeed fulfilled but nonetheless, today's consumer looks for maintenance-free service. His expectations with a propane vehicle will be no less optimistic and the hardware associated with propane must be developed to meet these demands.

Refueling with gasoline is taken for granted and the most significant changes in recent years, apart from cost, have been the transition to the metric system, the introduction of unleaded fuel, and the growing trend to self-service stations. Gasoline is also purchased in portable containers for lawn mowers, snow blowers and chain saws. Refueling and operating power equipment by young and old have become second nature and commonplace. In short, convenience and safety while handling gasoline and refueling a vehicle is not a matter of serious concern to the public.

On the other hand, the general public is not as familiar with propane and for that reason alone, some people are apprehensive about it. Any apprehension will not be allayed by the requirement in National Standard of Canada regulation, Can 1-B149.2-M80 that no passengers may be aboard when refueling a propane vehicle. Simplifying the refueling procedure for propane vehicles would be an important step in helping to get greater acceptance of propane as an alternative fuel.

When space cannot be found outside the body of a car for the propane fuel tank, it is often located in the trunk, limiting the amount of luggage that can be carried, a situation that might deter a vehicle buyer from opting for propane. An examination of techniques such as alternative-shaped fuel tanks to permit locating them in positions not now suitable for conventional tanks may be appropriate. Trucks, on the other hand, do not have the same constraints as passenger cars, either from space availability or weight considerations.

Mainly because of the weight of the fuel tank, a propane vehicle is heavier than its gasoline counterpart. Extra weight has a negative impact on a vehicle's performance and fuel economy and a study into alternative, lighter fuel tanks might permit a reduction in weight and improved fuel economy for a propane vehicle.

5.2 Tanks

5.2.1 General

Propane is carried on board a vehicle in a tank as a liquid. Although propane is a gas at atmospheric pressure, it remains a liquid in the tank under the influence of its own vapour pressure which varies from 100 kPa (zero gauge) at -42°C to 1 700 kPa at 50°C. A propane fuel tank is, therefore, a pressure vessel which must be designed accordingly. Most, if not all, present propane vehicle fuel tanks are designed according to specifications set up by the National Standard of Canada Canl-B 149.2-M80. This standard refers to the American Society of Mechanical Engineers (ASME) standards, and propane tanks in Canada are therefore often called ASME tanks. Federal law permits OEM companies to use non-ASME tanks (see section 5.2.4), but at the present time ASME tanks are used almost exclusively.

5.2.2 Alternative Tank Shapes

Since propane fuel tanks are pressure vessels, they are almost invariably cylindrical in shape with dished ends. Shapes other than cylinders cannot be ruled out, but apart from a sphere which is very costly, a cylindrical shape gives the best volume to weight ratio. The design formulae for cylinders are well understood and the manufacturing techniques firmly established so as to make them the most economical.

A cylinder does not always accommodate itself to the available space in a passenger car in the same way that a light gauge gasoline tank capable of a variety of shapes is able to do. This problem is aggravated by the thermal expansion and energy density characteristics of propane which necessitates large tank volumes in order to provide a range equivalent to gasoline. Propane tanks therefore often intrude into areas that could preferably be put to other uses. As cars become smaller, less space is available and the problem of locating the propane fuel tank becomes more difficult. There is a case to be made, therefore, for the use of unconventional shapes for propane fuel tanks to make use of the many irregular-shaped spaces inside and outside the passenger compartment.

It is unlikely that an irregular shape that meets the requirements of one car, would at the same time be readily accommodated by another. The cost of design, tooling, manufacturing and testing would then have to be borne by the volume of sales of that one vehicle, a factor which would probably make it economically unattractive. Conversations with tank manufacturers have sparked little interest and until a vehicle manufacturer proposes a

specific tank with some estimate of production volumes, the tank manufacturers are disinclined to get involved.

A type of irregular shape is already commonly used. Two or more tanks may be interconnected by rigid, integral, non-removable liquid and vapour passages and braced to form a single unit. Such a unit is commonly called a manifolded tank. Multiple single tanks are also frequently used, particularly for trucks and this also permits using variable size tanks in available spaces. It is not permissible to let propane flow from one tank to another where multiple single tanks are used and are interconnected by pipes or hoses; back check valves must be installed in each liquid withdrawal line.

5.2.3 Alternative tank materials

A propane vehicle generally weighs more than the same vehicle powered by gasoline because of the heavy steel propane tank. Table 6 indicates the weight of a Dodge 600 equipped for both propane and gasoline.

		GASOLINE	PROPANE	INCREASE
WT. OF CAR (less tank and fuel)	kg	1202	1202	---
WT. OF TANK	kg	10	32.3	22.3
WT. OF CAR PLUS EMPTY TANK	kg	1212	1234.3	22.3
CAPACITY OF TANK	Litres	49	62.9	13.9
WT. OF FUEL	kg	36	32	-4
WT. OF CAR PLUS FULL TANK	kg	1248	1266.3	18.3

TABLE 6 Comparative Weights for a Dodge 600 Equipped for Gasoline and Propane

The size of a propane tank is usually chosen so as not to diminish the range of the standard car built for gasoline and as pointed out in section 3.4.3, it takes approximately 20-27% more propane than gasoline on a volume basis to go the same distance. In this example the propane vehicle carries 62.9 litres of fuel or 28% more than the gasoline car and will therefore have at least the range of the gasoline car. The extra weight all comes from the propane fuel tank since propane is lighter than gasoline and 62.9 litres of propane weigh 4 kg less than the 49 litres of gasoline.

The weight of a vehicle affects acceleration, top speed, gradeability and fuel economy. Distribution of weight also has an influence on suspension and vehicle handling. Chrysler uses a computer simulation program to assess the effect of changes in weight on these aspects of vehicle performance and Table 7 shows the influence of increasing the weight of different size vehicles by 50 kg.

CAR WEIGHT	ACCEL. 0-100 km/h	TOP SPEED	FUEL CONSUMPTION SAE J 1082B	
			CITY	HWY
3000 LBS (1364 kg)	-3.2	-0.1	+1.37	+0.44
3500 LBS (1591 kg)	-2.7	-0.1	+1.17	+0.38
4000 LBS (1818 kg)	-2.4	-0.1	+1.03	+0.33
4500 LBS (2045 kg)	-2.1	-0.1	+0.91	+0.29

TABLE 7 Percent Change in Vehicle Performance when Weight is increased by 50 kg

Table 5 illustrates the point that a given weight change has a greater impact on smaller vehicles. An examination of these data can also give us an indication of what improvement can be expected from using lightweight materials for the propane tank used in the Dodge 600 E body car shown in Table 4.

The use of aluminum in place of steel is one approach to reduce weight by means of alternative materials. No aluminum tanks are built to ASME specifications, but aluminum propane cylinders for fork lift trucks and barbeques are widely used. It is estimated that the steel tank shown in Table 4, if made of aluminum, would weigh 22.6 kg for a saving of 9.7 kg. This weight saving would improve the car performance as follows:

- acceleration (0-100 km/h) 0.60%
- top speed negligible
- fuel consumption . city 0.26%
  . hwy negligible

The cost of the aluminum tank would be approximately 50% more than the cost of the steel tank and this cost penalty has to be measured against the gains from reduced weight. A review of the data forces one to conclude that a similar expenditure on engine performance might provide a more favourable cost/benefit ratio.

The TNO Research Institute for Road Vehicles in the Netherlands has conducted tests to evaluate whether there

are any unexpected problems with a propane-fueled vehicle involved in a fire. In 23 years experience, they have never known a fire to cause a tank to explode even though leaking LPG can cause carburetor or other fires in the same way as leaking gasoline (Ref. 34).

TNO burned two buses, one diesel powered and the other fueled with propane. The fires were started by simulated tire fires and allowed to burn unhampered. The fire in the diesel bus progressed slightly more rapidly than the propane bus but after 11 minutes, the temperature in each bus was 1 000°C. By 16 minutes both buses were completely burned out but the propane tank remained intact and the relief valve would blow off periodically to reduce the pressure built up by the heat.

In discussing with TNO the use of alternative materials for tanks, they pointed out again that temperatures of 1 000°C were reached at which some materials including aluminum might melt or weaken. The consideration of aluminum for a vehicle tank should, therefore, include an evaluation of whether it would involve any extraordinary risk in a fire situation.

Another approach would be the use of higher strength steels which would permit thinner materials and lighter tanks. There may be some room for improvement in this direction, although the present steels used are already of a high strength rating.

Composite fibreglass-wound light gauge tanks is another route that could be considered. Composite tanks are being developed for high pressure cylinders (20 000 kPa) but no work has been done with medium pressure tanks (2 000 kPa) probably because the cost would be prohibitive for the weight saved.

5.2.4 CTC Cylinders

Canadian Transport Commission (CTC) cylinders are designed as shipping containers for propane. They are not allowed to be used as fuel tanks in aftermarket conversions from gasoline to propane but vehicle manufacturers may use a CTC cylinder by meeting the barrier crash provisions of MVSS 301.1. Both steel and aluminum CTC cylinders are widely used for industrial or fork lift trucks and are usually mounted where they can be easily removed for filling.

The main objection to their use in vehicles is that all valves and connections are built into one end of the cylinder and are likely to be inaccessible or inconvenient for refueling purposes when permanently installed in a vehicle (Figure 30). Nevertheless, it may be quite practical for a vehicle manufacturer to design a CTC cylinder into a vehicle as a permanent installation, in which case

there would be a weight saving. For the Dodge 600 discussed earlier, the use of a steel CTC cylinder would save 3.7 kg. A CTC aluminum cylinder would be approximately 13 kg lighter than the steel tank specified.

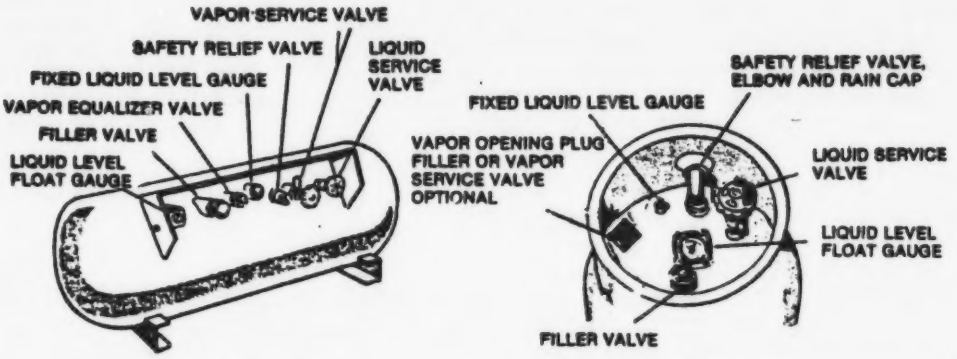

VAPOR SERVICE VALVE
SAFETY RELIEF VALVE
LIQUID SERVICE VALVE
FIXED LIQUID LEVEL GAUGE
VAPOR EQUALIZER VALVE
FILLER VALVE
LIQUID LEVEL FLOAT GAUGE
SAFETY RELIEF VALVE, ELBOW AND RAIN CAP
FIXED LIQUID LEVEL GAUGE
VAPOR OPENING PLUG FILLER OR VAPOR SERVICE VALVE OPTIONAL
LIQUID SERVICE VALVE
LIQUID LEVEL FLOAT GAUGE
FILLER VALVE
National Std of Can. Tank
C T C Cylinder

Figure - 30 - Arrangement of Valves on Tanks and Cylinders

5.3 Corrosion

Although tank corrosion is a factor accounted for in the design of ASME tanks, the hostile environment of Canadian winter roads is a good reason to give special consideration to anti-corrosion treatment of tanks mounted outside the passenger compartment and exposed to road splash. Many protective metallic and organic coatings such as galvanizing and epoxy coatings have been developed to protect steel in corrosive situations. An investigation into the most effective and economic protection for vehicle propane tanks would be appropriate.

As a first step, an investigation into the condition of propane tanks that have been in vehicle service for a number of years would be helpful in determining the extent of the problem. Accelerated laboratory tests could then be developed to duplicate the observed conditions of tanks in vehicle service and those tests used to evaluate alternative anti-corrosive treatments.

5.4 Refueling with propane

The most visible and functional difference between gasoline and propane-fueled vehicles is the refueling process. The propane fuel filler valve is mounted directly in the fuel tank or in some cases remote from the tank in order to have easy access to it. The filler valve incorporates a double check valve which allows liquid

propane to be pumped into the tank while preventing any liquid or gas from escaping.

Located adjacent to the filler valve is a bleed screw valve or fixed liquid level gauge. The bleed screw valve (often called a spit valve) is connected to a tube inside the tank located so that when the tank is 80% full, the end of the tube will be immersed in liquid propane. The propane tank must not be filled to more than 80% capacity as this leaves a space into which the liquid can expand if and when the temperature of the liquid increases.

When filling the tank through the filler valve, the bleed screw, which has a small orifice (1.4 mm), is opened and propane pumped into the tank until liquid propane spits out the bleed valve, giving visual indication that the tank has reached the 80% full level. Pumping is stopped and the bleed screw is closed.

There are no specifications for the design of the interface between the filler valve and the dispensing nozzle at the propane refueling station. In North America, and most parts of Europe, the filler valve has a large acme thread to which is screwed a coupling with matching threads on the end of the dispensing nozzle (Figure 31).

Some provinces including Ontario require trained, licensed attendants to dispense propane; self-service is not permitted. Heavy gloves are required to protect the attendant from cryogenic "burns" because liquid propane emitted from the spit valve or liquid propane trapped in the nozzle and then released when the nozzle is disconnected will expand into gas at a temperature of -42°C (Figure 32).

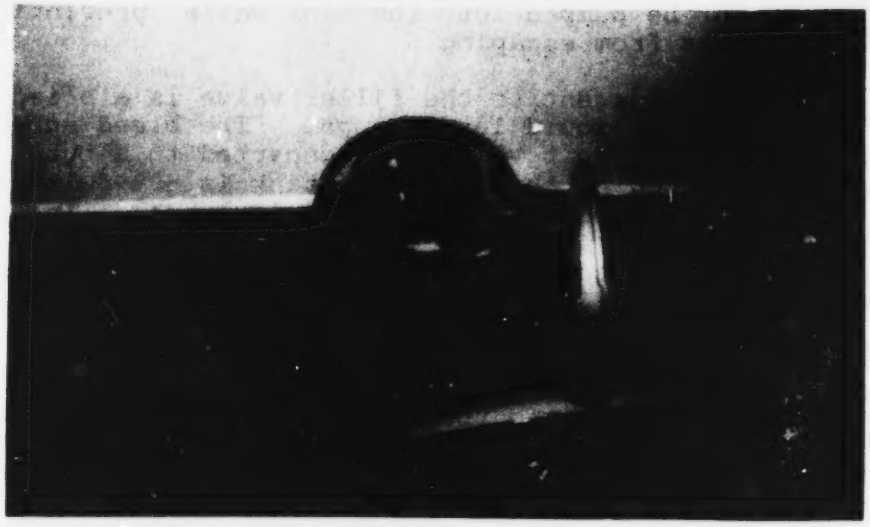


Figure 31 - Typical Propane Fuel Filling Port Showing Fill Valve and Spit Valve

Figure 32 - Operator Handling Fuel Filler Nozzle with Protective Gloves

It can be seen that refueling with propane is not quite the relatively simple procedure we are familiar with in refueling a gasoline vehicle.

Two changes to the filling procedure would go a long way towards simplifying the process; the use of a quick-disconnect dispenser and the elimination of the 80% fill limiting valve or spit valve.

The use of a quick-disconnect nozzle in place of the threaded coupling on the end of the dispensing hose would avoid having to unthread the coupling which exposes the refueling attendant to the small amount of liquid propane trapped in the nozzle when it is disconnected. Some installations use a second bleed valve to conduct the trapped propane away before unscrewing the coupling but that is a further complication.

In Europe, the self-service stations all use a quick-disconnect nozzle with no apparent problem, but it is necessary to screw an adapter to the tank fuel filler valve. The adapter is attached by a chain to the filler hose for the operator's convenience. Some filler valves in the Netherlands are designed to take the quick-disconnect nozzle without the need for an adapter.

There are a few refueling centres in Ontario using a different type of quick-disconnect nozzle which snaps directly over the acme threaded filler valve but all valves unfortunately are not dimensionally the same and as a result the nozzle does not fit over every valve being used. A coordinated effort on the part of nozzle manufacturers, valve manufacturers, motor vehicle manufacturers, and regulatory agencies is urgently needed to establish standards for nozzles and valves.

Present Canadian regulations permit vehicle manufacturers to build propane vehicles without spit valves if they use an 80% stop-fill valve which is usually a float-type valve similar in principle to the one used in a domestic toilet. Another design incorporates the spit valve and stop-fill valve together and senses the liquid propane coming out the spit valve to close the fill valve and stop the flow of propane into the tank. A design of stop-fill valve using an optical system has been developed in Europe, and has recently been made available in North America. Most European countries plan on making stop-fill valves mandatory, and their widespread use in Canada is almost assured once a reliable, cost competitive system becomes readily available.

During the refueling process, there are two ways in which propane escapes to the atmosphere. While fuel is being pumped in a certain amount of fuel is lost through the spit valve. This amount can vary substantially depending on the ambient temperature, the amount that the spit valve is opened and how fast the operator turns off the spit valve after liquid fuel starts being released from it. This release of fuel poses some fire hazard, although, in all fairness, it must be pointed out that when refueling with gasoline, vapour is also being forced out and any danger from fire is probably comparable.

The other loss of fuel occurs when the dispensing nozzle is uncoupled. There is some trapped liquid propane between the nozzle valve and the tank filler valve, the amount being variable depending on the type of nozzle. This not only wastes fuel but can be hazardous to an operator not wearing protective gloves. The problem of potential cryogenic "burns" for the operator makes the development and implementation of a minimum or no-fuel-loss nozzle a high priority with present refueling stations, and a virtual necessity if self-service type refueling outlets are to be introduced.

One approach that would prevent vapours escaping altogether would be the use of an expansion chamber connected to the tank. The connection would have a restriction that would allow slow expansion of liquid propane into the tank but prevent any significant flow during refueling. Figure 33 illustrates a version of this, which is an expansion tank within the fuel tank. B.K. Gas has developed this design but has dropped the project because of cost and weight. Another similar design, the Parkhill-Wade tank, has been marketed since the 1930's but no widespread use is apparent. Nevertheless, the principle has considerable attraction and if an economical design could be developed, it would be very much preferred to the stop-fill valve and/or spit valve arrangement.

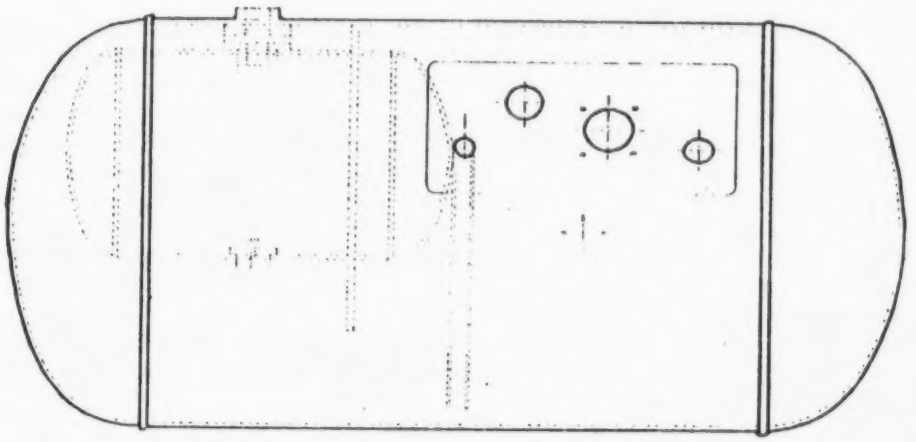


Figure 33 - Propane Tank With Internal Expansion Tank

The coordinated effort on behalf of all interested parties in establishing standards for fill valves and quick-disconnect nozzles should also address the possibility of having the 80% fill sensing mechanism as part of the filler nozzle along with a vapour return system. This would eliminate the need for a stop-fill valve in every tank and prevent the spillage of propane vapour

and liquid. Functional tests by regulatory authorities to give assurance that there is compliance with the 80% fill limitation would be greatly simplified.

Another item that appears to justify additional study is the requirement that propane tanks be purged of air before the initial fill. It is often disregarded, and to the best of our knowledge, this has never resulted in a problem. There is reason to suspect that it originated from a desire to hasten the attainment of stable fuel/air mixtures during initial operation of burners, then became confused with a safety requirement, and has been perpetuated mainly because challenging a "safety" rule involves more political risks than rewards. A preliminary study of the possibility of internal tank explosions has indicated not only that propane probably doesn't require purging, but suggests that gasoline, if analyzed in the same harsh manner, may appear to require it. Similarly, the contention that the space taken by the air justifies purging by aggravating pressure relief blow-off risks appears to depend on a very selective set of assumptions which exclude the consideration of some of the factors involved in a blow-off situation. A thorough examination of this requirement seems likely to lead to conclusive proof that it is unnecessary, wasteful, and in itself leads to other needless risks.

5.5 Welding Slag and Debris in Tanks

One last area that requires investigation and corrective action is the problem of welding slag and other particles in new tanks, which tend to plug the fuel filter within the first few thousand kilometres of operation. The problem is a more difficult one to solve than it first appears, since the welding slag tends to break off with vehicle vibration after the vehicle has been put into service. Slag accumulation is therefore normally quite high during the first 10 000 km of operation and may require the replacement of the fuel filter several times during this period. Once this initial period is over, dirt or slag accumulation in the fuel filter is rarely a problem, and normal maintenance intervals for cleaning or changing of the fuel filter will suffice.

A development program is needed to determine economical ways in which the slag can be broken loose after the tank is assembled and then removed through the relatively small fill hole.

5.6 Conclusions and Recommendations

(1) Alternative fuel tank shapes other than shapes based on cylinders or spheres are probably not economically viable at the production volumes projected for the immediate future.

(2) The use of alternative materials for tank construction could reduce overall vehicle weight but the performance and fuel economy benefits are not sufficient to justify any significant development cost or increase in tank cost. Comparable efforts and expenditure on engine systems will probably yield greater performance and fuel economy improvement.

(3) Any consideration for the use of aluminum as a tank material should include an evaluation of the tank in a fire situation.

(4) The use of CTC cylinders by vehicle manufacturers for permanent fuel tank installations may be practical and should be explored.

(5) The performance of propane fuel tanks in vehicle use from a corrosion standpoint should be evaluated. Alternative anti-corrosion treatments should be assessed and minimum standards established.

(6) The refueling procedure for propane vehicles is awkward and unlikely to inspire confidence in the safety of propane as a substitute for gasoline.

The development of simplified refueling procedures and standardized interfaces betweeen refueling equipment and vehicle equipment should be jointly undertaken by regulatory authorities, vehicle manufacturers, manufacturers of propane equipment for vehicles and manufacturers of dispensing equipment.

(7) The design and development of a compact, reliable 80% fill limiting system that does not require the emission of propane vapour or liquid is a high priority.

(8) The requirement that propane tanks be purged of air before the first fill appears unnecessary. Further study is needed to confirm this.

(9) A development program is needed to determine cost-effective methods for removing welding slag and other debris from new tanks.

6. DUAL-FUEL SYSTEMS

6.1 Overview

Once the decision is made to either buy a propane-powered vehicle or convert a gasoline vehicle to propane, there is a choice between single-fuel propane or dual-fuel gasoline/propane. There are certain attractions to a dual-fuel system:

- it retains a large portion of the economic advantage of using propane for the major part of the vehicle's use.

- it avoids the risk of propane not being available when needed.

- there may be more resale opportunities for a dual-fuel vehicle than one equipped only for propane.

On the other hand a dual-fuel vehicle has a number of drawbacks:

- most dual-fuel systems available today will give performance and fuel economy that are not as good as when the vehicle is built to use either fuel alone. The compromise is usually in favour of gasoline at the expense of the propane mode and this can give the owner a poor impression of propane as a fuel.

- a dual-fuel system means increased weight since both fuel systems including tanks, and in most cases fuel, have to be carried. This reduces vehicle performance and fuel economy.

- the need for two fuel systems, particularly tanks, creates space problems. In a single-fuel propane system, the propane tank can sometimes be located in the same space occupied by the gasoline tank. When the gasoline tank is retained additional space must be given up.

- when the propane system is designed and built into the vehicle by the vehicle manufacturer, it would be more costly to provide both fuel systems. For an aftermarket conversion, dual-fuel systems are no more costly than a single-fuel system since all of the gasoline system hardware is already in place.

- most jurisdictions have no exhaust emission regulations covering propane vehicles and exhaust emission hardware is therefore not supplied with single-fuel propane vehicles. On the other hand

converting a vehicle to dual-fuel does not invalidate the requirement to meet emission regulations in the gasoline mode of operation. This puts even more complexity and compromise on the system than is necessary or required with a single-fuel propane version.

- gaskets tend to dry out and cause leaks when the gasoline system is used after a period of propane operation.

- the number of service problems will likely be the sum of those experienced by either fuel alone and there may be additional ones resulting from interaction of the two systems.

If we compare these lists of advantages and disadvantages, the number alone seems to come down in favour of single-fuel propane systems. And yet, in Europe, except for France, all systems are aftermarket dual-fuel versions. Economies resulting from taxation policies in Europe explain why the aftermarket carries out the installation rather than the vehicle manufacturers but it is not the reason for building dual-fuel vehicles. The overriding concern in Europe is that propane/LPG will not be readily available wherever and whenever needed. This concern prevails despite the widespread availability in Italy and the Netherlands but less so in other countries.

It is a valid concern, for the best operating vehicle in the world is not much use if there is no fuel available when it is needed. And this concern will probably deter many vehicle owners in Canada from turning to propane. There is, therefore, a case to be made for providing dual-fuel vehicles to encourage those interested in using propane but fearful of the risk. Having once tried a dual-fuel vehicle they may find their operating pattern never takes them to areas where propane is unavailable and they can choose for their next vehicle a single-fuel propane version.

6.2 Dual-Fuel Alternatives

If dual-fuel systems are to be built, it should be done in such a way as to minimize the disadvantages of present dual-fuel systems by designing the vehicle primarily for propane with gasoline as the secondary fuel. Compromises therefore should be made as much as possible to benefit propane at the expense of gasoline.

If it is recognized that a dual-fuel vehicle is just a step on the road to more widespread use of propane, a part of government policy aimed at making Canada self-sufficient in oil, then relaxation of the exhaust emission

requirements for the gasoline operating mode would be appropriate. It is probably safe to say that after paying a premium price for purchasing the propane fuel option, the owner would operate the vehicle on propane whenever possible. It also follows that since propane is readily available in most urban areas, virtually all city driving would be done on propane. The most likely situation for the owner to switch to gasoline would be in extended out-of-town highway driving, where a propane re-fueling station may not be available. In this case, the emissions penalty for running on gasoline would be minimal, since most gasoline vehicle emissions are substantially lower in steady state highway driving than in city driving, especially during cold weather conditions. Potential adverse effects of such emissions occurring in less populated areas will also be of minimal concern compared to similar emissions in urban areas. The relaxation of gasoline emissions standards for the dual-fuel vehicle, therefore, would probably have a minimal effect on the environment, but give the manufacturer considerable flexibility in designing an optimum system.

The main aim would be to optimize the propane mode, and compromises should be in the direction that favours propane at the expense of gasoline, whenever possible. This would encourage the operator to use propane wherever possible and to use gasoline only when absolutely unavoidable. Two approaches suggest themselves:

- designed primarily for propane operation with a limited range, limp-home capability with gasoline

- designed primarily for propane operation but with as few compromises with gasoline as possible to permit respectable performance with gasoline.

6.2.1 Limp-Home Capability With Gasoline

This approach is in line with the use of small size emergency spare tires that are not intended for prolonged use but only to get home or to a service station. The vehicle operator would be satisfied to use gasoline in an emergency but the performance, driveability, and fuel economy would be inferior to propane and he would revert to propane at the earliest opportunity. Such a system might embody the following features:

- no exhaust emission controls

- reduced size gasoline tank to provide space for a propane tank and also to give only limited range with gasoline.

- increased compression ratio to take advantage of propane's high octane rating, although possibly

lower than that attainable with a propane-specific vehicle.

- premium gasoline required.

- a dual spark timing program, one optimized for propane and the other severely retarded for gasoline to avoid detonation because of the increased compression ratio. A knock sensor may be required.

- deletion of the intake air heat stove to help volumetric efficiency when using propane.

- deletion of the intake manifold heat crossover or a manual control if it is found that the crossover is necessary for acceptable and safe performance with gasoline.

- incorporation of a wide open throttle lockout to prevent wide open throttle operation on gasoline. (To minimize detonation caused by the higher compression ratio)

- incorporation of all engine durability components necessary for propane.

6.2.2 Full Range Capability With Gasoline

This approach is similar to the limp-home version, but although the system would be designed primarily for propane, and that would be the preferred mode, there would be fewer disadvantages operating with gasoline than in the limp-home version, and the range of the vehicle would not be restricted. It is likely that a lower compression ratio engine than is used in the limp-home system would be required. The system might embody the following features:

- no exhaust emission controls

- increased compression ratio to take advantage of propane's high octane rating but low enough to permit operation with premium gasoline when a knock detector is fitted.

- a dual spark timing program, one optimized for propane, the other designed for gasoline, using a knock detector to retard timing when necessary to prevent detonation.

- intake manifold heat crossover would be retained but manually or automatically blocked when in the propane mode.

- the intake air heat stove would be retained but not used in the propane mode.

- incorporation of all engine durability components necessary for propane.

In either of the above cases, the gasoline fuel system could consist of a carburetor, or a single or multi-point fuel injection system. At first glance, it would appear that the carburetor would be the logical choice for the gasoline system, having the lowest cost of the three. However, due to recent cost reductions, single-point fuel injection systems are likely to achieve widespread use in gasoline-fueled vehicles in the near future. Use of these single-point fuel injection systems for the gasoline mode may also hold significant advantages over a carburetor in terms of ease and smoothness of switching the system from gasoline to propane and vice versa.

Regardless of the gasoline fuel system chosen, whether carburetor or fuel injection, both of the two approaches to dual-fuel vehicles described above appear to be viable choices.

6.3 Conclusions and Recommendations

(1) Dual-fuel systems will always be a compromise between what can be achieved with either fuel alone.

(2) Dual-fuel systems may be a helpful introduction to propane systems for that segment of the public who would not otherwise venture to buy a propane-powered vehicle.

(3) A dual-fuel system could likely be developed to give near-optimum performance with propane and still provide an emergency fall-back system of limited range and performance with gasoline.

(4) A dual-fuel system could likely be developed to give superior performance with propane and still provide acceptable range and performance with gasoline.

(5) On the assumption that dual-fuel vehicles are a step towards gaining acceptance of single fuel propane vehicles, all exhaust emission regulations should be waived.

(6) If a point is reached when all of the automotive propane can be used in single-fueled vehicles, dual-fuel systems will represent a waste of both fuel and hardware.

7. LOW TEMPERATURE CONSIDERATIONS

7.1 Overview

The Canadian winter has always posed formidable problems for motor vehicles. Equipment and systems found to be perfectly satisfactory in the United States and Europe have often proved inadequate in the much lower temperatures often experienced in Canada. Special consideration has had to be given to Canadian vehicles with respect to engine start-up, heater and defroster performance, engine lubricants, brake fluids,and gasoline vapour pressure. A whole catalogue of auxiliary cold weather equipment has evolved including radiator winter fronts, battery warmers, heavy-duty batteries, block heaters and oil heaters. It is safe to say that the average motorist in Manitoba and Saskatchewan becomes very knowledgeable about his vehicle's cold temperature capabilities and limitations and he learns by experience how to cope with the problems of severe winter weather.

Cold ambient temperatures pose problems to all internal combustion engines. Increased oil viscosity adds greatly to engine and transmission friction, imposing much heavier cranking loads on the starting motor and unless the engine turns over at sufficient speed, it is difficult to start. The problem is compounded by the lower battery voltage available at low temperatures. In consistently cold areas, this situation is addressed by using a 5W grade engine oil, a heavy-duty battery and a block heater. At low cranking speeds, the metering of fuel (liquid or gaseous) is very imprecise making it difficult to obtain a combustible mixture in the cylinder. Driveline friction and tire rolling friction are greatly increased and take many miles to stabilize, causing higher fuel consumption and increased exhaust emissions. Since it takes longer for the engine to warmup and the cold ambient temperature imposes a greater task, heater and defroster performance are severely tested.

Automotive propane equipment has been, for the most part, developed in Europe and the United States, and it would be surprising if some cold weather problems were not encountered when this equipment is used in Canada. Experience is still limited but during the winters of 1981-82 and 1982-1983, Chrysler Canada carried out on-road cold weather testing with propane-fueled vehicles at Kapuskasing, Ontario. Chrysler Canada in a joint effort with Transport Canada has also carried out a cold room test program during 1982.

Although a substantial amount of development and testing remains to be done enough is known to indicate the areas where propane is superior to gasoline in a cold

environment and where improvements are needed. The vehicle operator will always compare the performance of his propane-fueled vehicle with his past experience and with the present performance of his colleagues and neighbours driving gasoline-powered vehicles. The goal for a propane-fueled vehicle operating in cold weather is for it to be equal to gasoline vehicles in all areas and be superior in some.

The most significant difference between gasoline and propane vehicles will be related to the low temperature properties of the two fuels along with the fuel handling and metering equipment of each. The specific areas where differences might be expected are:

- start and warmup
- fuel-air ratio requirements
- driveability
- fuel consumption
- exhaust emissions

7.2 Start and Warmup

Since a propane-fueled vehicle has no fuel pump and depends on the tank vapour pressure to feed liquid propane to the vaporizer, the boiling point of the fuel determines the lowest temperature at which fuel can be delivered to the vaporizer. Pure propane has a boiling point of -42°C, but small amounts of ethane and propylene which have lower boiling points will add sufficient tank pressure to permit fuel delivery at slightly below -42°C. Nevertheless, it would be prudent to assume that without a minimum ethane fuel content, or auxiliary means of delivering fuel, -40°C is the temperature limit at which fuel delivery can be assured.

It is important to recognize that it takes at least twelve hours exposure at -40°C for the fuel tank temperature to reach that level. If, for instance, the ambient temperature overnight dropped from -20°C to -40°C, the temperature of the various components of the vehicle, including the fuel tank, will be several degrees higher. For sustained ambient temperatures below -40°C, an electric blanket or similar device would ensure sufficient tank pressure to start and run the engine. Whether the tank would retain pressure when the vehicle is on the road would depend on the ambient temperature and the location of the tank in the vehicle. When considering seasonal blend fuels (Section 8), the provision of additional quantities of ethane, which has a vapour pressure of 630 kPa at -42°C, during the winter months would be helpful. Chrysler Canada experience during road tests is that a propane vehicle will drive satisfactorily once the engine has been started and warmed up with as little as 20 kPa gauge pressure.

Assuming that there is enough tank pressure to deliver liquid propane to the vaporizer, there must be sufficient heat transfer in the vaporizer to vaporize the propane. At temperatures between -10°C and -20°C, problems which can be attributed to insufficient heat transfer begin to show up. Typically, the engine will start and then stall a few seconds later when the available propane vapour is used up. This condition is referred to as a "freeze-up" by field personnel. Most of these occurrences do not involve freezing of any kind. Freezing only occurs when incorrect glycol mixtures are used. Most often, the condition is caused by the vaporizer's inability to supply enough gaseous propane to meet the engine requirements. This results in an accumulation of liquid propane in the vaporizers' heat exchanger that stalls the engine and effectively inhibits restarts thus lending the impression of a "freeze-up". With the best present systems, warmup problems do not occur above -10°C. It is not uncommon, however, to have difficulty at much higher temperatures with some aftermarket conversions. It is likely that with enough development, warmup problems with propane could be effectively eliminated for all temperatures where engine cranking speed is high enough for the engine to have reliable starts (overnight lows in the -30°C range).

Tests by Chrysler Canada have shown that with a block heater, no problems during start and warmup are encountered down to ambients of -35°C, the lowest temperature at which tests were carried out. It is probable that a block heater will eliminate start or warmup problems down to the lowest temperature at which fuel can be delivered to the vaporizer. When start and warmup comparisons are made between vehicles using the same fuel or between the same or similar vehicles using different fuels, it is extremely important that the test conditions be exactly the same. As already implied, a cold room test during which the vehicle has been soaked at -30°C for sixteen to twenty hours (standard test condition) is much more severe than an overnight soak outside when the ambient drops through the night to -30°C. The oil viscosity for each vehicle must be the same; the battery voltage available must be the same. Nevertheless, even when all test conditions are precisely controlled, a propane-fueled engine may respond a little differently from one using gasoline. In a gasoline engine during cold weather, despite positive crankcase ventilation, there is some dilution of the oil with unburnt fuel which lowers the viscosity of the oil and makes the engine easier to crank. Similarly, when starting a gasoline engine, the choke is closed and a large amount of liquid fuel finds its way into the cylinders, diluting or washing down the oil on the cylinder walls, thereby reducing the engine friction. With propane there is no crankcase dilution and being metered as a dry gas, propane leaves the oil film on the cylinder walls undisturbed. For

these reasons, at low temperatures an engine may crank more slowly when using propane instead of gasoline.

With gasoline, a carburetor choke is required for starting and warmup. As the engine comes up to operating temperature, the choke gradually comes off and the fuel-air ratio slowly changes from very rich to its warmed-up mixture setting. With propane, a primer is used to help starting at low temperatures, but once the engine starts, the amount of fuel being metered is independent of engine and ambient temperature. Except for the variability of air density with temperature, the fuel-air ratio will therefore be the same at all temperatures and in general will provide a better combustible mixture in the cylinder than gasoline at low temperatures. Propane can also provide better cylinder-to-cylinder distribution at all temperatures but especially so at low temperatures when the choke is in operation on a gasoline engine.

A gasoline carburetor incorporates a multi-step fast idle cam or automatic idle speed system to provide greater air and fuel flow during warmup. This is required to overcome cold engine friction and maintain a satisfactory idle speed. Many commercially available propane systems do not have a fast idle system and depend on the operator to maintain his foot on the accelerator during warmup. This is not satisfactory and a fast idle device should be designed into the system to overcome cold engine friction.

Once a propane engine has reached a warmed-up condition, tests by Chrysler Canada have shown the drive-ability of a well-designed system to be excellent down to ambient temperatures of -35^{o}C.

7.3 Fuel Consumption

Although propane has a greater heating value than gasoline on a mass basis, 46.2 MJ/kg vs 43.3 MJ/kg, because of its lower density it has only 75% of the heating value of gasoline on a volume basis. One would expect therefore that volumetric fuel consumption using propane would be 1/.75 = 33% more than gasoline. Because of better engine efficiency, however, the differential between propane and gasoline is usually on the order of 20% (city driving) to 27% (highway driving) in warm ambient temperatures (Section 3.4.3).

In cold ambients, propane performs even better compared to gasoline, particularly during warmup, when gasoline requires a carburetor choke to give enriched mixtures until normal engine operating temperatures are reached. Because of higher engine and drive line friction, increased tire rolling resistance, and higher aerodynamic drag, all vehicles will experience higher fuel consumption in cold ambient conditions regardless of fuel used, but

propane has a smaller increase than gasoline. Since a great deal of urban driving involves short trips, propane compares very favourably in that type of service, particularly in the winter.

7.4 Exhaust Emissions

Propane has long been the preferred fuel for fork lift trucks operating inside factories because of the very low levels of carbon monoxide emitted. In general, unburnt hydrocarbons also tend to be lower and the emissions from propane engines are usually less reactive than from gasoline. Nitrogen oxide emissions from propane engines are about the same or sometimes higher than from gasoline.

All emissions tests use closely controlled ambient temperatures around 25°C and only limited data is available for vehicles operating at low ambients. Nevertheless, we do have some data on emissions from propane vehicles at low ambient temperatures. In tests conducted jointly with Transport Canada in their cold room in Blainville, Quebec, a propane vehicle was tested along with a similar gasoline vehicle at temperatures of +25°C, 0°C, and -20°C. The results showed no increase in HC and CO emissions between +25°C and 0°C for the propane vehicle, with emissions increasing below 0°C. Overall, the increases in emissions for the propane vehicles were much less than for the gasoline vehicle. This is primarily related to the effect of the choke on the gasoline vehicle at low temperatures. As temperatures decrease, the choke on the gasoline vehicle remains on for a longer period of time, resulting in increased hydrocarbon and carbon monoxide emissions. Propane vehicles, on the other hand, do not require a choke and hence HC and CO emissions do not increase nearly as rapidly with decreasing temperature, compared to gasoline.

Tests conducted by the U.S. Bureau of Mines showed similar results. Figure 34 (Ref. 35) shows the effect of ambient temperatures on exhaust emissions for propane, natural gas and gasoline over the relatively narrow range of -6.7°C to 35°C (20°F - 95°F). These data represent the average of many vehicles used in several programs at the Bartlesville Energy Centre of the U.S. Bureau of Mines and clearly demonstrate the rising trend of carbon monoxide and unburnt hydrocarbons from gasoline as ambient temperatures get lower, whereas emissions when using propane are relatively constant over the temperature range.

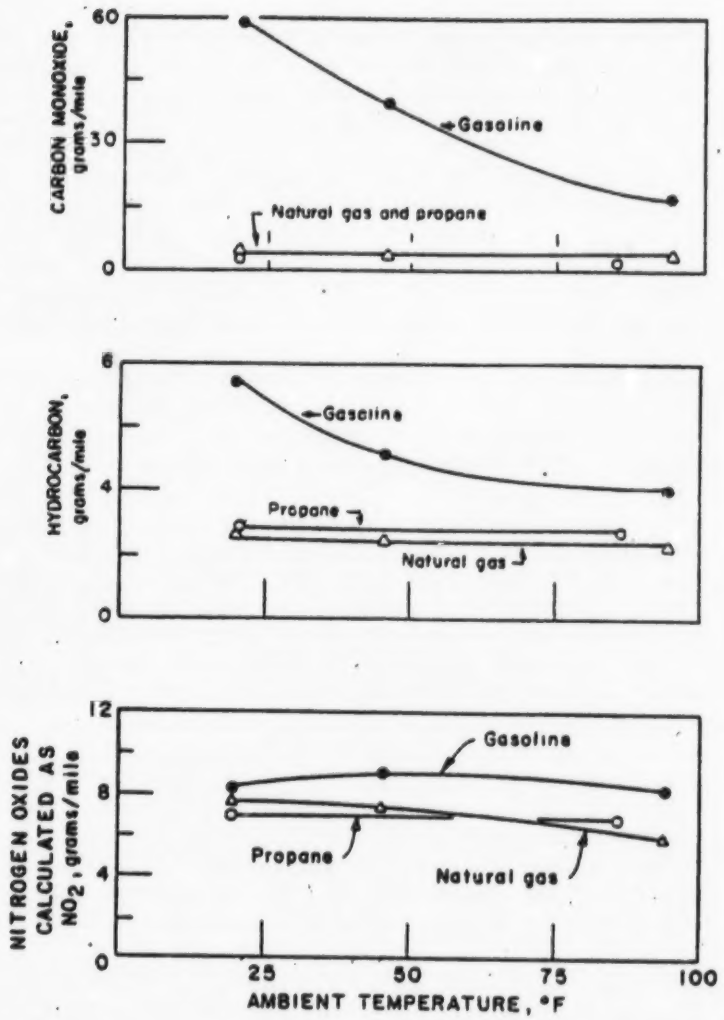


FIGURE 34 - Effect of Ambient Temperature on Emissions of Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides for Gasoline, Propane, and Natural Gas. (Ref. 35)

7.5 Conclusions and Recommendations

(1) The best presently available propane systems usually demonstrate deficiencies at ambient temperatures below -15°C.

(2) Propane systems can be developed to eliminate warmup problems down to the lowest temperature at which the vehicle would reliably start (without the aid of a block heater).

(3) When a block heater is used, no start or warmup problems have been encountered with present systems at temperatures as low as -35°C. It is probable that with a block heater, engine start and warmup would be satisfactory down to the coldest temperature fuel could be delivered.

(4) Without an assured ethane fuel content, or auxiliary heat applied to the fuel tank, there will probably be insufficient vapour pressure to supply the engine with fuel below -40°C.

(5) At low ambient temperatures, propane-fueled engines likely have more friction than gasoline-fueled engines. Test work should be carried out to determine the cranking requirements of propane engines at low ambients to ascertain whether there needs to be modification to oil viscosity, starter motor torque, or battery capacity.

(6) From a fuel consumption standpoint, propane has an advantage over gasoline during short trips and cold ambient temperatures because no carburetion choke is required for starting or warmup. A more comprehensive assessment of this advantage could be made using Transport Canada fuel consumption test cycles and on-road operation.

(7) Carbon monoxide and hydrocarbon emissions are low at all ambients when propane is used, but the improvement over gasoline is particularly pronounced at low ambient temperatures during start and warmup and for short trips.

8. PROPANE FUEL BLENDS

8.1 Overview

In many parts of the world, LPG is used as an automotive fuel without specifying its composition. The constituents are mainly propane and butane with smaller percentages of propylene, butylene, and ethane. The make-up of LPG varies from country to country and is largely determined by what is being produced at the refineries and/or natural gas wells. In colder climates, the proportion of propane is increased to maintain tank pressure. As an example, in Sweden LPG consists of 85-95% propane while in Italy propane constitutes only 20% of LPG. In the Netherlands, the proportion of propane/butane varies by season; in winter it is 60/40; in the summer it is 40/60. B.K. Autogas, the largest retailer of automotive LPG in the Netherlands, specifies a minimum vapour pressure of 0.6 bar gauge (60 kPa) at -15°C for the months of December, January, and February. In the southern United States it is common for LPG with high quantities of butane to be used instead of automotive grade propane and ASTM is presently surveying the market practices in the U.S.A. to determine what is being sold across the country for automotive use.

This raises the question whether some relaxation of the automotive grade propane specification might be appropriate in Canada, particularly with regard to butane content. It has been suggested that a summer grade of fuel with a lower vapour pressure would create no technical problems and would permit propane producers more latitude in blending the fuel during the warm months when there is a low demand for butane as a heating fuel. Seasonal blends of fuels are not new because the specification for gasoline vapour pressure varies seasonally to permit easier starting in the winter and to prevent vapour lock during the summer.

The establishment of the automotive grade propane specification was, in the main, directed at limiting the propylene content in order to preserve the anti-knock quality of the fuel. The limit of 5% maximum propylene still seems to be appropriate, particularly since higher compression ratios are being contemplated to take advantage of the superior octane value of propane. This discussion will, therefore, consider only the implications of varying the relative amounts of propane and butane.

8.2 Properties of Propane/Butane Blends

Table 8 lists the important properties of automotive grade propane (CGSB-Grade 1) which contains 2.5% butane and compares those properties with five LPG blends containing increasing amounts of butane (10% to 50%). The assumption that butane is equally divided between n-butane and iso-

butane may not be precisely correct but the small differences in vapour pressure and density resulting from this will have no significant effect on these results. Ethane is also present in automotive propane in small amounts and is limited by the maximum vapour pressure permitted at 38°C. No account is taken here of the ethane content; any amount present will partially compensate for the lower vapour pressure due to substituting butane for propane.

In considering the motor octane value, if all butane were n-butane, the octane rating of a 50% butane blend would be 91.5 instead of 93.5 when the butane is split evenly between n-butane and iso-butane. This is perhaps the greatest area of concern with fuel blends containing high percentages of butane. The problems that this causes, and possible solutions, are discussed later in this section.

	FUEL BLEND					
	* 1	2	3	4	5	6
PROPANE (percent)	92.5	85	75	65	55	45
PROPYLENE (percent)	5	5	5	5	5	5
n-BUTANE (percent)	1.25	5	10	15	20	25
iso-BUTANE (percent)	1.25	5	10	15	20	25
VAPOUR PRESSURE (gauge) at 38°C - kPa	1198	1135	1049	965	880	795
RELATIVE LIQUID DENSITY at 15.5°C (BLEND 1=1.0)	1.00	1.01	1.02	1.04	1.05	1.06
RELATIVE VAPOUR DENSITY at 15.5°C (BLEND 1=1.0)	1.00	1.02	1.06	1.09	1.12	1.15
STOICHIOMETRIC FUEL-AIR RATIO	.064	.064	.064	.064	.064	.064
NET HEAT OF COMBUSTION Mj/kg	46.2	46.2	46.1	46.1	46.0	45.9
Mj/Litre @ 15.6°C	23.6	23.8	24.1	24.3	24.6	24.9
MOTOR OCTANE NUMBER	95	95	94.5	94	94	93.5

* AUTOMOTIVE GRADE PROPANE: CGSB - GRADE 1
All fuel blends assumed to contain 5% propylene
Butane content assumed to be 50/50 n-butane/iso-butane

TABLE 8 Important Properties of Propane/Butane Blends

In evaluating butane blends, the major points to consider are:

- Variations in F/A ratio. What will be the effects of the richer F/A ratios caused by increasing the butane content of the fuel?

- Cold weather operation. What is the lowest temperature at which there will exist sufficient vapour pressure to permit fuel delivery to the vaporizer, and what is the lowest temperature at which the vaporizer will perform satisfactorily with the blends considered?

- Motor octane rating of the fuel. What will be the effect of increasing butane content on the octane rating of the fuel, and how will this affect the design of the engine?

At 15.5°C, the most dense fuel blend considered, 50% butane, is 6.3% heavier and contains 5.5% more energy per unit of volume than Grade 1 automotive propane. Even more important, however, the same blend has a vapour density 15% greater than Grade 1 fuel. This is important because the fuel is metered to the engine as a vapour. Since the stoichiometric or chemically correct fuel-air ratio for butane is very close to propane's, an increase in fuel vapour density will result in a proportionately richer fuel-air ratio being metered to the engine. Theoretically, if the fuel-air ratio was corrected for each blend, a 5.5% improvement in fuel consumption would be possible with blend 5 due to the higher energy content of the fuel. If the carburetor was not adjusted for each blend, no fuel consumption benefit would be realized and there could be a fuel consumption penalty with the butane blends.

The following chart shows the effect that the butane blends, shown in table 8, would have on fuel-air ratio, assuming the carburetor was calibrated for stoichiometric operation using grade 1 fuel.

	BLEND					
	1	2	3	4	5	6
FUEL-AIR RATIO	.064	.065	.068	.070	.072	.074
EQUIVALENCE RATIO Fr	1	1.02	1.06	1.09	1.13	1.16

Under cruise conditions, most carburetors are calibrated to run leaner than stoichiometric. In the case of Chrysler's 5.2 L propane engine, for example, equivalence ratios of 0.87 are normal under cruise conditions. In this case, use of the butane blends would make the mixture richer, although up to blend #5 it would still be leaner than the stoichiometric fuel/air ratio. The effect of making the mixtures richer would be to increase carbon monoxide emissions and also possibly increase fuel consumption as stated earlier.

Under conditions of wide open throttle, the carburetor may be calibrated to run slightly richer than stoichiometric to obtain maximum power. In this case, delivering an even richer mixture would cause some losses in power. The exact amount would have to be determined on an engine dynamometer for each engine and would depend on the previous level of enrichment.

It is of interest to note that since, in most cases, mixtures will be leaner than stoichiometric with the fuel blends shown, use of an oxygen feedback system to control the F/A ratio to a stoichiometric ratio would not likely provide any improved economy when fuel blends are used, and would likely increase fuel consumption when Grade 1 fuel is used.

Figure 35 shows the vapour pressure versus temperature for CGSB-grade 1 propane and blend 6 of table 9 containing 50% butane; vapour pressure for blends 2 to 5 fall within the values shown. For blend 6, the vapour pressure down to -20°C would appear to be adequate to deliver fuel to the vaporizer. On the other hand, it is doubtful that currently available carburetion equipment would give satisfactory performance at that temperature with blend 6. As discussed in section 7, engine warmup problems begin to show up at about -10°C when using CSGB grade 1 propane; at what temperature a fuel having a high content of butane would have problems is uncertain. Below the boiling point of n-butane (-0.5°C), it is probable that some liquid butane would pass through the vaporizer into the carburetor causing extremely rich mixtures. Cold weather test and development work needs to be carried out to determine the low temperature limits of various butane blends.

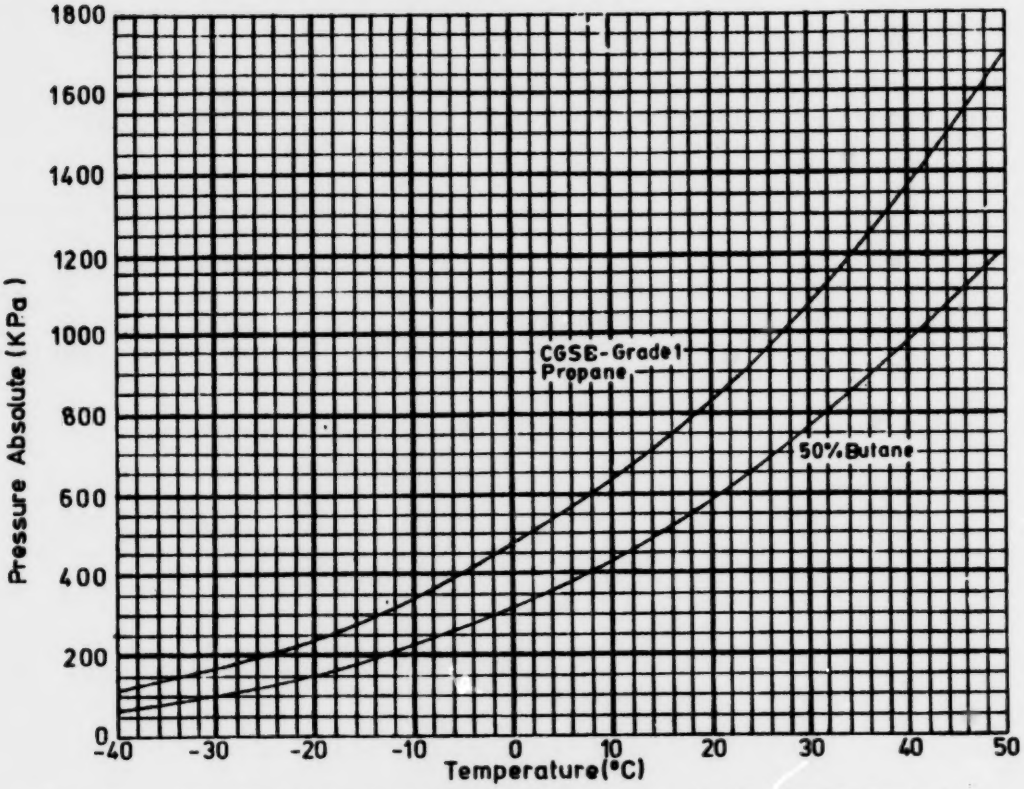


Figure 35 Vapour Pressure Vs Temp. Of 2 Blends Of LPG:CGSB Grade 1 Propane And A Blend Of 50% Butane

It is interesting to note that B.K. Gas, the largest distributor of automotive LPG in the Netherlands, has a specification during the winter months of 60 kPa at $-15^{o}C$. At that temperature a blend of 50% butane has a vapour pressure of 85 kPa. It is tempting to leap to the conclusion that if a 60 kPa fuel at $-15^{o}C$ is satisfactory for Holland in winter, then an 85 kPa fuel should be adequate for the summer season in Canada. However, almost all cars in Europe using LPG have dual-fuel systems and cold weather problems may be covered up by starting the engine on gasoline and switching to propane after the engine is warmed up.

Probably the most important aspect of high butane content fuel blends is the resultant lowering of the octane rating of the fuel. As discussed earlier, a 50% butane blend would have an ON of 93 if there was a 50% split between iso-butane and n-butane, and a 91.5 ON if all the

butane was n-butane. Many present LPG engines have higher compression ratios than the equivalent gasoline engine, and with their spark timing set for optimum power and efficiency, it is likely that this blend would cause engine failures if all the butane was n-butane.

If butane blends were to become a reality, it would be necessary to 1) specify a minimum MON for the fuel, and 2) design all engines for this minimum MON.

Specifying a minimum MON would allow the use of butane blends while guarding against high percentages of low octane n-butane. In this way it would be possible to design engines compatible with butane blends with as little compromise in compression ratio and spark timing as possible, and therefore obtain a balance between maximum use of butane and maximum engine efficiency.

8.3 Conclusions and Recommendations

(1) The use of propane-butane blends appears practical for Canadian summer temperatures, providing minimum octane requirements are implemented.

(2) The use of high percentages of butane in LPG would necessitate a lowering of the compression ratio and/or retarding of the spark timing from that achievable with Grade 1 fuel.

(3) By instituting a minimum MON requirement for butane blends, it would be possible to obtain a balance between the maximum use of butane and maximum engine efficiency, with a minimal compromise in engine efficiency.

(4) The use of high percentages of butane in LPG would likely cause some increase in fuel consumption and loss in power output for an engine calibrated for Grade 1 fuel, the exact amount depending on the engine and fuel calibration used.

(5) Great care would have to be taken with the propane supply system to ensure that blends with high butane content were not introduced too early in the year or retained too late in the year so that starting and running problems are avoided during a sudden drop in the temperature.

(6) Test work should be carried out to determine the practical temperature limits for various propane/butane blends.

(7) Increased amounts of propylene beyond 5 per cent should not be allowed.

(8) The use of a closed loop feed-back system would not likely provide decreased fuel consumption with increased butane content.

(9) Cold area winter blends could use higher percentages of ethane to provide sufficient tank vapour pressure to start and run a propane-fueled engine below -42°C.

(10) The use of butane blends appears to have good potential for extending the automotive supply of propane/LPG.

9. HEALTH AND SAFETY CONSIDERATIONS

9.1 General

The LPG/propane industry is a mature one with well-defined and organized systems for control, distribution and use of its products. This section will not, therefore, attempt to cover all aspects of the handling of propane from the producer to the consumer. Instead, the differences between gasoline and propane will be highlighted primarily to reassure the motorist who has no experience with propane and is considering using propane as an alternative fuel in his vehicle.

The questions that might be of concern to a motorist who has had no previous experience with propane are:

- what are the risks of fire?
- is propane gas poisonous?
- in a collision, is there any greater danger with propane?
- how do exhaust emissions compare with gasoline?

Any concerns the motorist may have stem largely from propane being relatively unknown to him.

9.2 Combustion and Flammability

Propane is a fuel widely used for heating and is obviously highly combustible, as are gasoline and natural gas (methane). Natural gas is familiar as a home heating fuel. None of these should be allowed to be introduced to a closed area where there is a possibility of any spark or open flame. The flammability limits of natural gas are somewhat wider than for propane and gasoline, which are similar (Table 9 ,Ref. 36). Natural gas, being lighter than air, will rise and disperse more readily than propane, which, being heavier than air, tends to hug the ground. Gasoline vapour is heavier than propane and also tends to gather in low areas.

	RELATIVE DENSITY AIR=1	IGNITION TEMP. (^{o}C)	FLAMMABILITY LIMITS IN AIR % TOTAL VOLUME
NATURAL GAS	0.55	705	5.0 - 15.0
PROPANE	1.56	466	2.1 - 10.1
GASOLINE VAPOUR	3.80	425	1.4 - 7.6

TABLE 9 Comparative Flammability Properties of Natural Gas, Propane and Gasoline (Ref. 36).

Another measure of fire hazard is to identify the amount of ventilation air required per litre of fuel vapour released in order to prevent fire. The values for the three fuels are:

for methane - 20.0 litres of air
for propane - 47.6 litres of air
for gasoline - 71.4 litres of air

In summary, all three are combustible fuels which are extremely flammable. They should be treated and used with the utmost care and common sense.

9.3 Toxicity

Hydrocarbons such as natural gas, propane and gasoline vapour are simple asphyxiants. They have no specific toxic effect but act by excluding oxygen from the lungs. Their effect is proportional to the extent they diminish the amount of air breathed. Oxygen may be diminished by one third before appreciable symptoms develop (Ref. 37).

Clearly these gases are not intended to be inhaled, but they are not poisonous or corrosive in the sense that carbon monoxide or ammonia are poisonous. The threshold level value (TLV), the concentration to which workers may be exposed day after day without adverse effect, is an indication of the relative danger of various gases. The TLV value for carbon monoxide is 50 parts per million (ppm) and for propane 1000 ppm. Gasoline, being of variable composition, has no set TLV but since it will contain varying amounts of aromatic hydrocarbons the TLV can be assumed to be lower than propane (Ref. 37).

Natural gas and propane have odorants added so that the presence of the gas in air is detectable. Long before propane could become dangerous as an asphyxiant, its presence would be very noticeable and offensive to smell.

The danger with propane from fire exceeds by far any danger from asphyxiation.

9.4 Fuel Handling and Transportation

Propane must be stored and transported in pressure vessels, either CTC cylinders or ASME tanks which are protected by shut-off valves, back check valves and pressure relief valves. As with all pressure vessels, they must be handled carefully and not abused. The National L P Gas Association in the United States has published an L P Gas Safety Handbook which covers all aspects of the regulatory and recommended practices in the handling and transportation of propane (Ref. 38).

Apart from its flammability, the property to be careful about when handling propane is its boiling point. Liquid propane at normal atmospheric temperature in a cylinder or tank will drop to its boiling point -42°C when released to the atmosphere. This must be recognized when releasing propane for any reason and suitable protection against freezing exposed parts of the body, particularly the fingers, must be taken.

The degree of convenience or difficulty when refueling with propane are discussed in section 5.3. Any inconvenience is largely the result of precautionary measures to avoid filling the fuel tank more than 80% full and to prevent cryogenic "burns" (freezing). As dispensing hardware is developed and alternatives to the fixed liquid level gauge are designed, the refueling process will become more convenient.

Tests carried out by TES Ltd. during their Gas Powered Vehicle Evaluation Program for Transport Canada (Ref. 39) pointed out that propane and gasoline both required careful attention to proper procedures but that neither was significantly more dangerous than the other during refueling.

9.5 Propane Vehicles Involved in Crash Situations

Vehicle crash situations involving gasoline-fueled cars or trucks do not often result in fire but when they do, the results can be dramatic. If the gasoline tank leaks or bursts it poses a tremendous hazard. The public is, therefore, understandably concerned about how a propane vehicle performs in an accident situation. Is it a greater hazard than a gasoline vehicle?

Since the Netherlands has approximately 10% of its cars being run on LPG, the TNO, Research Institute for Road Vehicles in Delft, conducted extensive vehicle-to-vehicle crash and barrier crash tests to evaluate the safety of these vehicles. The tests and results are described in detail in a paper given at the Symposium on Non-petroleum Vehicular Fuels in Arlington Virginia in 1980 (Ref 34). Their conclusions are:

- The automotive LPG tank was able to withstand all impacts without leakage of the tank itself. In some cases when an appurtenance was hit, small leakage at this appurtenance occurred.

- Even with impact by a wedge-shaped piece of steel on a tank mounted on an immovable barrier no leak occurred in the tank despite severe damage. During one such test a small leak in an appurtenance was caused.

- LPG-fueled cars are safer than gasoline-fueled cars in a crash situation.

One case was cited wherein a car was struck by two trains, one shortly after the other and the only part of the car left intact after the crashes was the LPG tank.

During the project by TES Ltd., which evaluated propane, gasoline and CNG-powered vehicles (Ref. 39), two vehicles with each of the fuel systems (a total of six vehicles) were crashed. None of the gasoline or CNG-fueled vehicles released fuel or experienced any fire. Both propane systems leaked fuel at a slow rate due to severed lines or snapped fittings but the vapour dissipated without fire or explosion and the tanks continued to leak until empty. TES Ltd. concluded that the test results were applicable only to the particular vehicle and the specific tests and also pointed out that locating and installing the tanks were carried out as conversions. They felt that vehicle manufacturers might choose different locations and installation techniques which would influence the results.

9.6 Exhaust Emissions

This subject has also been discussed briefly in sections 6.2 and 7.5. Many results have been published in the literature attesting to the lower exhaust emissions when propane is used instead of gasoline (Refs. 5,8,11,13,21,40). In particular, carbon monoxide emissions are much lower with propane. The general acceptance and understanding of this fact is responsible for its widespread use in forklift trucks. Engines can operate over a wider range of fuel-air ratios with lower carbon monoxide and hydrocarbon emissions than when using gasoline. Since mixture enrichment is unnecessary during cold start and warm-up with propane, it eliminates the emission penalty experienced with gasoline during those modes of operation. Furthermore, the photochemical reactivity of hydrocarbon emissions from propane is considerably lower with propane than with gasoline (Ref. 35). Oxides of nitrogen are about the same or tend to be a little higher when propane is used.

Although it is well understood that propane is clean burning with low exhaust emissions, the actual emissions from any individual vehicle will depend on the condition of the engine, the quality of the propane carburetion equipment, and the quality of the installation. As changes are made to optimize an engine for propane, such as increasing the compression ratio and establishing spark timing schedules for best performance and best fuel economy, the effect of the changes should be evaluated.

9.7 Conclusions and Recommendations

(1) Propane poses no greater fire or explosion hazard than gasoline or natural gas. All fuels must be handled with care and only approved techniques and containers used.

(2) Propane is not poisonous per se and as an asphyxiant is no more dangerous than natural gas.

(3) Refueling systems, hardware and techniques presently used for propane are unlikely to inspire confidence or a sense of security in those using propane. There is a strong need to develop simpler systems that lend themselves to self service, which is becoming the norm for gasoline refueling.

(4) Well-designed propane-powered vehicles are safer than gasoline-powered vehicles in a crash situation.

(5) Exhaust emissions can be, and tend to be, lower when using propane, particularly carbon monoxide emissions. The actual values vary widely depending on the quality of the equipment and installation.

10. PROPOSED R & D PROGRAM

The following sections outline the proposed research and development program for the optimization of propane-fueled engines and fuel system components. The program is broken down into individual development groups, each of which could be done separately. The groups are ranked by priority in table 10 at the end of the report.

10.1 Compression Ratio Development

Objective

Using Grade 1 fuel determine the maximum practical compression ratio for a production engine based on:

- tooling limitations
- design limitations
- durability
- knock limited compression ratio
- hot startability
- combustion considerations
    - squish distance
    - swirl versus no swirl

Determine F/A ratio and spark advance requirements for compression ratio chosen.

Procedure

DESIGN:

Perform design work necessary on a present production gasoline engine to determine the maximum obtainable compression ratio and the method used to obtain it. Consideration should be given to:

1) Tooling limitations. Only casting and tooling changes which can be economically justified in terms of future production potential should be considered.

2) Design limitations. Minimum design clearances will have to be maintained between the piston and the valves or cylinder head, for safe high speed operation.

3) Durability. Initial selection of the compression ratio should be kept below levels that, based on past experience, would be expected to cause major engine damage. Subsequent engine testing may necessitate a re-design of certain components, or a lowering of the compression ratio, to achieve acceptable durability. (See also section on Engine Durability Development.)

4) Combustion considerations. It will be necessary to determine the minimum squish distance for propane and the effect of swirl on the combustion of propane, since both of these factors will affect the maximum compression ratio achievable. Dynamometer testing, therefore, will have to be conducted concurrent with design work to determine the maximum compression ratio for the engine selected.

DEVELOPMENT:

1) Squish Distance

Select an appropriate compression ratio based on the above design considerations. Design two or more sets of pistons to give different squish distances while maintaining the same compression ratio. Determine the minimum acceptable squish distance for the engine by measuring, on an engine dynamometer, torque, BSFC, and other appropriate variables with each set of pistons.

In each case, squish should be kept above the minimum distance required for safe high speed engine operation.

Compare data from dynamometer runs to determine the minimum recommended squish distance.

2) Swirl

a) Design and develop a combustion chamber with the desired amount of swirl. (To minimize testing required, assume same swirl rate as gasoline, or if other data is available at the time, assume some other swirl rate for propane.) With the squish distance selected above, determine the maximum compression ratio possible with a swirl chamber by increasing the compression ratio in small increments and repeating dynamometer tests until the knock limited compression ratio is reached, or until design constraints limit the compression ratio obtainable.

b) Redesign chamber and/or ports to obtain minimum or no swirl. Repeat dynamometer tests at same compression ratios as in 2(a) above, and determine the knock limited compression ratio.

Based on the data from all tests conducted, compare designs of swirl vs no swirl to determine the optimum chamber shape and compression ratio.

Perform CVS city and highway cycle tests to determine the fuel consumption benefit of the design selected over the standard compression ratio gasoline engine running on propane.

10.2 Carburetion Development - F/A Ratio Control

Objective

To demonstrate improvements that can be made in fuel consumption, power and driveability by modifications to existing carburetion equipment.

Procedure

1) Select a commercially available carburetion system, based on dynamometer and/or on-road tests, which already provides acceptable fuel consumption and driveability and which has the capability to be modified in terms of F/A ratio control.

2) Design and develop modifications to the carburetion system chosen to satisfy the engine F/A ratio requirements determined in section 10.1, and provide optimum fuel consumption and driveability.

   Changes may include:

   (a) Power Enrichment:

   The carburetion should be designed to provide maximum power F/A ratio during wide open throttle or near-wide open throttle operation. A staged power enrichment circuit to provide richer-than-cruise but leaner-than-maximum power enrichment at medium throttle conditions is a possibility.

   (b) Improved Lean Cruise Mixture Control:

   The carburetor should be designed to provide optimum (lean) F/A ratios under cruise conditions.

   (c) Deceleration Leaning or Fuel Shut-off:

   The design could include provisions for lean mixtures or complete fuel shut-off on decelerations for improved economy.

   (d) Electronic Controls:

   A design could be developed to provide open-loop electronic carburetion controls to provide optimum F/A ratio for most operating conditions based on inputs of throttle positions, manifold vacuum, inlet air temperature and pressure etc.

The above modifications should be developed and evaluated simultaneously on an engine dynamometer and on the road.

3) Evaluate improvements in fuel consumption and driveability by performing CVS city and highway cycle tests and by conducting on-road driveability evaluations.

10.3 Carburetion Development - F/A Distribution

Objective

To improve engine performance and fuel consumption through improved F/A distribution.

Procedure

1) Evaluate, on an engine dynamometer, various readily available types of intake manifolds (dual plane, single plane, others), and limited modifications to the manifolds, if required, to determine the best manifold for F/A distribution.

2) Perform modifications to the carburetor to improve F/A distribution, if required.

3) Evaluate the benefits of the changes made by performing part throttle and WOT runs on the engine dynamometer and measuring BSFC and torque.

10.4 Carburetion Development- Vaporizer Sludge Formation

Objective

To determine the cause of sludge formation in the vaporizer

To develop hardware to minimize the accumulation of sludge in the vaporizer, or develop systems to automatically drain the sludge from the vaporizer if deemed necessary

Procedure

1) Analyze several samples of sludge from vaporizers to determine composition of sludge and possible sources.

2) Perform the following tests to determine the effect of vaporizer operating temperature on sludge formation.

a) Use three engines with a common supply of Grade 1 propane. Operate the three engines at a steady state part throttle condition or through a predetermined load cycle. Control the coolant temperature supplied to the engines. Maintain all engine temperatures the same, while maintaining the coolant temperature to the three vaporizers at 65°C, 95°C and 110°C respectively.

Fuel lines used should be metal wherever possible. A minimum of elastomeric hose should be used to avoid the possibility of leaching out the plasticizers in the hose. A fourth engine could be run, if judged appropriate based on the test results from item 1, with all elastomeric fuel lines to evaluate their effect on sludge formation.

b) Record the fuel used by each engine.

c) Measure sludge buildup in the three vaporizers.

d) Determine the sludge formed per unit of fuel used and the relation to vaporizer operating temperature.

3) Perform development work on a vaporizer to minimize sludge formation or accumulation if deemed necessary based on the above tests.

This may include:

- Use of a thermostat to lower vaporizer operating temperature.
- Modifications to the vaporizer to allow sludge to be passed through and burned in the engine.
- Design of a sludge recovery system to automatically remove sludge as it accumulates.

10.5 Ignition System Development - Spark Plug Heat Range

Objective

Determine spark plug heat range required for the engine/compression ratio developed in section 10.1.

Procedure

Run engine on dynamometer at compression ratio, spark advance and carburetion selected earlier in sections 10.1, 10.2, and 10.3.

Perform testing to select the correct heat range spark plug according to industry standard practices.

10.6 Ignition System Development - Voltage Requirements

Objective

Determine ignition system voltage requirements for the engine/compression ratio developed in section 10.1 and determine if present ignition systems are capable of meeting those requirements.

Procedure

Run engine on dynamometer at compression ratio, spark advance, carburetion, and correct heat range spark plug selected earlier in sections 10.1, 10.2, 10.3, and 10.5.

Under conditions of part throttle, WOT, and transient operation determine ignition system voltage requirements at selected spark plug gaps. Repeat test with ignition systems (including plugs, distributor cap and distributor leads) that have 25 000 km and 50 000 km metrage accumulation on them.

Modify ignition system to accommodate voltage requirements if necessary. (Modifications could include: changes to the coil, distributor or spark plug gap.)

10.7 Valve Timing Development

Objective

To improve fuel consumption through valve timing changes.

Procedure

Evaluate, on an engine and chassis dynamometer and on the road, camshafts designed to improve fuel consumption through improved idle quality and lower idle speeds. A primary area of change is likely to be reduced valve overlap.

1) On-road Evaluations

On-road evaluations of camshafts designed to improve idle fuel consumption should proceed simultaneously with engine dynamometer evaluations of the same camshaft.

On-road evaluations will provide a subjective evaluation of improvements in idle quality and changes in WOT performance. These improvements in idle quality should then be translated into further improvements in fuel consumption by lowering the idle speed.

Potential problems that may limit the idle speed available include:

- body resonant vibrations caused by the lower frequency engine vibrations.
- oil pumping limitations
- coolant pumping limitations
- electrical charging limitations

Where economically justifiable, changes should be made to overcome these problems as they arise.

2) Engine Dynamometer Testing

The proposed camshafts should be evaluated on an engine dynamometer at idle, part throttle, and WOT to provide data on the magnitude of changes in fuel consumption and power output.

3) Chassis Dynamometer Testing

CVS testing should be performed with the selected camshaft(s) to determine the city and highway cycle fuel consumption benefit.

10.8 Engine Durability Development - Valves and Valve Seats

Objective

To determine methods for achieving valve and seat wear comparable to what is obtained on unleaded gasoline fueled engines.

Emphasis should be placed on:

(1) Determining cost-effective methods for achieving acceptable wear rates.

(2) Determining if fuel or oil additives are required to achieve acceptable wear rates.

Procedure

1) Engine Dynamometer Testing

Engines should be run on an engine dynamometer using an appropriate durability schedule.

Items to be investigated could include:

- alternative seat insert materials;
- effect of seat angle on wear;
- effect of type of rotation on wear (may include tests where valve is keyed to provide no rotation);
- effect of tolerances (valve guide to seat concentricity, etc.) on wear;
- effect of temperature on seat wear;
- effect of valve material or valve facing material on seat wear;
- effect of engine oil additives on wear;
- effect of fuel additives on wear;
- effect of using additional alloying elements in present induction-hardened cast iron head;
- use of "layered" inserts with harder material on seating surface of insert to reduce costs;
- possibility of welding a thin layer of hard facing material on the cylinder head valve seat surface (cast iron heads only).

An investigation of valve dynamics using high-speed photography could also be performed if deemed necessary.

2) Vehicle testing

Several vehicles should be equipped with the best packages developed above and field tested to determine the valve and seat durability in actual on-road use.

The outcome should be:

(a) a selection of valve and seat design which is best suited for propane-fueled engines.
(b) a determination of whether fuel or oil additives are needed to control wear, and if so, which ones are most appropriate.

10.9 Engine Durability Development - Piston Rings

Objective

To determine the optimum ring package for propane. Selection of the ring package will depend largely on the tradeoff between the long-term durability of the rings and their ability to break-in easily.

Procedure

Run engines on a dynamometer and on the road with various ring packages to determine the ability of the rings to break-in easily on propane. The analysis should include a comparison of chrome-plated and tin-plated top compression rings.

Perform extended durability tests on an engine dynamometer to determine the durability of the various ring packages selected.

10.10 Engine Durability Development - General Engine Durability

Objective

To determine the overall engine durability at the compression ratio chosen and compare it to the equivalent displacement but lower compression ratio production gasoline engine. Where deficiencies exist the problem should be corrected, or, if this is not possible because of tooling limitations, cost, etc., the optimum lowered compression ratio should be determined.

Procedure

1) Using standard engine dynamometer durability test schedules, evaluate the overall durability of the engines selected. Where deficiencies exist development should be initiated to correct the problem or the compression ratio should be lowered.

2) After completion of the dynamometer tests, engines should be evaluated for durability over a minimum 100 000 km road test.

10.11 Engine Oil Development

Objective

Determine whether conventional SF motor oils provide adequate service when used in propane-fueled engines, and if not, develop an SF rated motor oil that does.

Procedure

1) Evaluate one or more conventional SF motor oils in both gasoline and propane-fueled vehicles to establish baseline data for analysis and further testing. This should be done by operating a fleet of gasoline and propane vehicles in both city and highway service and in summer and winter using appropriate laboratory tests to measure engine oil deterioration over a minimum of 12 000 km. Laboratory test results should be compared between the gasoline and propane vehicles to determine whether conventional SF oils are acceptable for propane applications.

2) If the conventional SF oils are determined to be inadequate for use in propane-fueled engines, repeat the above tests on the propane-fueled vehicles only, using alternative oil formulations.

3) Using industry standard tests evaluate any selected oils for SF rating requirements.

During all the above tests, valve recession measurements should be made at the start and end of each test to provide information on the effect of oil additives on valve seat wear.

10.12 Fuel System Development - Container Shapes and Materials

Objective

PART A:

Evaluate alternative fuel container configurations and compare to ASME tanks in terms of:

- tooling and piece costs
- space saving potential
- weight savings

PART B:

Evaluate alternative fuel container materials, and compare to the steels presently approved for use in ASME tanks in terms of:

- weight savings
- cost savings
- corrosion resistance

Procedure

PART A:

1) Determine piece cost and tooling cost for alternative fuel container shapes.

2) Perform a stress analysis to determine the minimum wall thickness and structural integrity of shapes chosen.

3) Compare alternative shapes selected on the basis of cost, weight, and space saving potential.

PART B:

1) Evaluate cost and weight saving potential of alternative container materials. These may include:

   - aluminum
   - stainless steel
   - higher strength steels
   - composite materials

2) Evaluate formability or manufacturability of alternative materials.

3) Where appropriate, evaluate corrosion resistance of alternative tank materials through salt bath and other tests.

10.13 Fuel System Development - Corrosion

Objective

Determine the life expectancy of present steel tanks under Canadian driving conditions

Evaluate various corrosion protection techniques which could be used for extending the life of externally mounted steel tanks.

Determine in-service safety inspection procedures and inspection intervals for re-certifying tanks in service.

Procedure

Fuel Tank Materials and Corrosion:

1) (a) Perform a field survey of propane vehicles with internally and externally mounted ASME steel tanks that have been in use for a minimum of 5 years. Remove tanks on selected vehicles and perform a visual check as well as a hydrostatic test on each.

(b) Perform accelerated corrosion tests on vehicles with externally mounted ASME steel tanks and compare with data from the field survey above.

(c) From the data gathered estimate the life expectancy of a steel propane tank in service.

2) Based on the best available information, select coatings, treatments, or new tank materials to minimize corrosion of tanks.

3) Evaluate proposed coatings, treatments or alternative tank materials against standard steel tanks in accelerated corrosion tests, and project useful life of new tanks versus standard tanks.

In-service Inspection Procedures and Intervals:

1) Select or develop an economical in-service inspection procedure for re-certifying the safety of tanks in service.

This could include such items as:

- a visual inspection of tanks on the vehicle
- hydrostatic testing of the tanks on or off the the vehicle
- an X-ray or ultra-sound evaluation of tanks on or off the vehicle

- some other appropriate process of checking tanks on or off the vehicle

2) Determine an appropriate inspection interval for carrying out the procedure selected above.

10.14 Fuel System Development - Refueling Hardware

Objective

Find or develop an improved fuel filling nozzle, suitable for self-service use, which is safe and convenient to use and which allows minimum or no fuel spillage.

The nozzle should be able to be used without the operator wearing a protective glove.

Procedure

1) Evaluate all presently available filling nozzles for safety as follows:

(a) measure the amount of fuel spillage that occurs when the nozzle is bled off or disconnected from the vehicle;

(b) determine if the fuel spillage above is likely to contact a person's skin if they are holding the nozzle without gloves. If the nozzle has a bleed mechanism it should be evaluated with and without the use of this prior to removal;

2) Evaluate all nozzles for ease of use by equipping vehicles with each type of nozzle and performing a survey of gasoline vehicle owners to determine which is most convenient to use.

3) If no nozzle is judged acceptable by the above tests, perform design modifications to existing nozzles or design new nozzles which achieve desired levels of safety and convenience. Priority should be given to designing a nozzle that has as close to zero fuel spillage as possible.

10.15 Fuel System Development - Automatic Stop-fill Systems

Objective

Find or develop a system which accurately and consistently shuts off fuel delivery to the vehicle at a predetermined fill level.

Procedure

1) Evaluate all currently available systems to determine if they meet the following performance criteria:

   a) must consistently shut off fuel flow to the tank at the set level + or - 5% of the tank water capacity at all practical fill rates.

   b) must perform satisfactorily at temperatures from -50°C to +100°C and humidity levels up to 100%.

   d) must perform satisfactorily for 200 000 km or five years in service, whichever comes first.

   e) must meet the requirements of the Underwriters Laboratories Inc. and the relevant Canadian Gas Association standards.

2) If no system is found acceptable, design and develop a stop-fill valve that meets the above criteria.

10.16 Fuel System Development -- Welding Slag and Debris in Tanks

Objective

Determine cost effective methods for removing welding slag and other particles from inside of the tank, after welding is completed.

Procedure

Using production propane fuel tanks, evaluate various methods of removing slag and other particles from tanks. This may include methods such as vibrating the tank (low frequency, ultra-sound etc.) and removing the debris by air, liquid or other means.

A cost analysis should be made for each method tested and the best method(s) selected by a cost versus results analysis. Completed tanks should then be evaluated on vehicles to determine if the problem has been resolved.

10.17 Dual-Fuel -- Compression Ratio Development

Objective

PART A: FULL-RANGE CAPABILITY WITH GASOLINE

Determine the maximum practical compression ratio for a dual-fuel engine running on gasoline, assuming:

- no emissions constraints
- premium fuel
- knock sensor ignition system
- minimal driveability penalty versus standard compression ratio gasoline engine

PART B: LIMP-HOME CAPABILITY WITH GASOLINE

Same objective as above except assume moderate to severe driveability penalty is acceptable.

Procedure

PART A: FULL-RANGE CAPABILITY WITH GASOLINE

Design and Development:

1) Engine Dynamometer Testing. Begin testing with the engine and compression ratio selected earlier in section 10.1.

   Using premium fuel and utilizing carburetion for the standard compression ratio gasoline engine, determine the knock limited spark advance at part throttle and WOT.

   Evaluate modifications which may minimize spark knock. These may include the use of EGR at part throttle and WOT.

2) Driveability. Perform driveability tests concurrent with engine dynamometer tests to determine:

   a) the level of driveability penalty associated with the spark retard used, and

   b) any preignition that may occur in actual on-road driving under hot, dry weather conditions.

Evaluate driveability results and dynamometer data to determine if the compression ratio is acceptable or whether it should be decreased.

Decrease the compression ratio and repeat dynamometer and road tests if:

a) preignition is found to be a problem

b) the amount of spark retard required is judged unacceptable for durability reasons

c) driveability is unacceptably poor

Perform CVS fuel consumption and emissions tests on a vehicle in both gasoline and propane modes.

PART B: LIMP-HOME CAPABILITY WITH GASOLINE

If the final compression ratio selected in part A is the same as the compression ratio for the dedicated LPG engine in section 10.1, then part B work is not required. If it is lower than the compression ratio selected in section 10.1, then the following work should be carried out.

Design and Development:

Increase the compression ratio over the ratio selected above and repeat dynamometer and road tests.

Evaluate the use of a wide-open-throttle lock-out to minimize detonation.

Maintain the selected compression ratio and stop testing if:

(a) moderate to severe driveability penalty is experienced, or
(b) the compression ratio chosen is judged the highest acceptable for durability reasons.

Increase the compression ratio and repeat tests if:

(a) driveability is not significantly different from the standard compression ratio gasoline engine, and
(b) the knock limited spark advance is not significantly retarded from the MBT advance

Abandon part B tests if durability of the engine is judged to be severely compromised because of preignition or other problems.

Perform CVS fuel consumption and emissions tests on a vehicle in both gasoline and propane modes.

10.18 Dual-Fuel - Ignition System Development

Objective

Develop a dual timing curve spark control computer with the following features:

- it must have separate governor and vacuum advance curves for gasoline and propane which can be independently calibrated.
- it must have knock sensor capability in the gasoline mode. Knock sensor capability in the propane mode is optional.
- with an external signal or input the computer should switch from gasoline to propane timing and vice versa.

Procedure

1) Perform electronic design and development work to accomplish the above objectives.

2) Verify operation of the computer on a scope and/or on a vehicle.

10.19 Dual-Fuel - Hardware Development - 1

Objective

Evaluate the driveability penalty associated with not having intake manifold heating on a dual-fuel vehicle operating in the gasoline mode. Assume the intake air heat stove is required on gasoline for acceptable operation of the vehicle.

Develop automatic switching hardware to switch on or off the following items when switching from gasoline to propane and vice-versa.

- -intake air heat stove
- -intake manifold heating (if required based on driveability testing)
- -EGR system (if used - see section 10.17)

Procedure

1) Perform driveability tests at temperatures down to -20°C at varying humidity levels, with and without intake manifold heating, to determine the penalty associated with not having this feature.

   All tests to be run with the intake air heat stove functioning and the EGR system (if used) operating.

2) Develop switching hardware to switch on or off the intake air heat stove, intake manifold heating system and EGR system as required when switching from one fuel to another.

10.20 Dual-Fuel -- Hardware Development - 2

Objective

Develop an automatic fuel control system which provides smooth and reliable switching from gasoline to propane operation and vice versa, with minimum driver input.

Procedure

Because of the increasing use of gasoline throttle-body injection systems, this section will only consider dual-fuel systems incorporating throttle-body injection and will not include a discussion of a dual-fuel system incorporating a gasoline carburetor (see also section 6.2.2).

The system should be designed such that the operator only has to operate one control for the vehicle to switch from gasoline to propane operation and vice versa. The dual-fuel control system should automatically drain or fill the gasoline fuel system so that a smooth transition takes place.

The system should also be designed, if possible, such that the electronics controlling the propane fuel system (spark advance and fuel control) are separate from the gasoline electronics and not an integral part of the gasoline system. A substantial amount of work developing an interface system which couples the separate gasoline and propane electronics will therefore have to be done. This will allow greater flexibility in applying the outcome of the development work to more than one manufacturer, and will probably be most representative of the way in which dual-fuel would be handled in the relatively low volumes forecast for the immediate future.

10.21 Low Temperature Operation - Vaporizer Development

Objective

To develop a propane carburetion system capable of meeting fuel vaporization and delivery requirements under Canadian winter conditions.

Emphasis should be placed on improving the "start-and-run" performance of propane vehicles at ambient temperatures below -15°C (without the aid of a block heater).

Procedure

Design and develop changes to the carburetion system which will improve the cold start performance of the vaporizer and fuel system.

Changes may include:

- Changes to the vaporizer to improve the heat transfer from the coolant to the fuel. Changes may be made to the coolant-to-vaporizer housing interface, and/or to the vaporizer housing-to-propane interface.

- Changes in coolant flow paths from the engine to the vaporizer or coolant flow rates through the vaporizer.

- Use of 12 V heater elements to aid in fuel vaporization before or after a start.

- Use of a vapour start system.

The benefit of any changes made should be evaluated by cold room engine dynamometer testing as well as by on-road testing at temperatures of -15°C and below.

10.22 Low Temperature Operation - Cold Cranking and Starting

Objective

To determine the optimum F/A ratio and spark advance settings for cold starting

To compare cold cranking requirements to gasoline and determine if propane-fueled engines require engine oils with a higher viscosity index or require other changes for acceptable cold weather cranking.

Procedure

1) Perform the following tests on an engine in a cold room. Ambient temperature to be controlled to -25°C with adequate soak times provided between successive cold starts.

   a) With the spark advance fixed at 10° BTDC, perform successive cold starts on the engine at different F/A ratios. Measure time to start and determine optimum F/A ratio.

   b) With F/A ratio fixed at the optimum selected above, vary the S/A and measure time to start.

2) With S/A and F/A ratio selected above, vary soak temperature and determine minimum temperature and corresponding cranking speed at which the engine will start. Compare cranking speeds to gasoline and determine if the lack of engine oil dilution with propane requires a higher viscosity index oil or other changes for acceptable cold cranking.

10.23 Fuel Blends

Objective

To determine practical fuel blend limits for engines which have spark timing and fuel/air ratio schedules calibrated for Grade 1 fuel, but are running on propane/butane blends, by examining the effects of fuel blends on vehicle performance, fuel consumption and driveability.

Develop carburetion and other hardware to provide satisfactory engine operation on various fuel blends, if required.

Determination of the maximum practical compression ratio for each blend should not be an objective of this section due to the extensive testing required. Testing should be limited to determining what carburetion and spark timing modifications, if any, are required for operation of present generation propane engines on fuel blends.

Based on the results of section 10.1, a theoretical calculation could be performed to determine the approximate compression ratio and fuel consumption penalty associated with the lower octane rating of each fuel blend.

Procedure

1) Engine Dynamometer Testing

(a) Run engine on Grade 1 fuel at part throttle and WOT with carburetion and spark advance calibrations developed for Grade 1 fuel.

Measure: BSFC and F/A ratio at part throttle; Torque and F/A ratio at WOT.

(b) Repeat (a) for each non-Grade 1 fuel blend without changing the carburetion and spark advance calibrations.

(c) Develop carburetion and spark advance calibrations for each fuel blend using the same procedure used for Grade 1 fuel.

Run engine at part throttle and WOT with carburetion and spark advance calibrations developed for each blend.

Measure: BSFC and F/A ratio at part throttle; Torque and F/A ratio at WOT.

2) Chassis Dynamometer Testing

Run city and highway cycle CVS tests:

(a) Using Grade 1 fuel with carburetion and ignition calibrated for Grade 1 fuel. (Same calibration as in 1(a) above.)

(b) Using fuel blends with carburetion and ignition calibrated for Grade 1 fuel.

(c) Using fuel blends with carburetion and ignition calibrated for each fuel blend. (Same calibrations as in 1(c) above).

3) Warm Weather Driveability Testing

Perform driveability tests on vehicles with fuels and calibrations used in 2 (a), (b) and (c) above.

4) Hardware Development

Analyze results from previous tests to determine:

(a) The potential benefit of a control system to correct F/A ratio for each fuel blend used.

(b) The need for a detonation sensor or other control system to control spark advance for each fuel blend used.

Develop above control systems, if required. Repeat engine dynamometer, chassis dynamometer, or driveability tests as required to determine benefit of carburetion and ignition modifications.

5) Low Temperature Driveability Testing

Perform driveability tests with fuel blends at temperatures down to -20°C without the aid of a block heater. Use the hardware developed in item (4) above, or if no hardware developed use existing hardware calibrated for Grade 1 fuel.

Use a driveability schedule with moderate to heavy accelerations shortly after cold starts to accentuate any "start-and-run" problems that may be associated with the fuel blends.

Investigate fuel tank heaters, mechanical fuel pumps, etc. as devices to assure fuel delivery at low temperatures if required.

Analyze results to determine lowest recommended operating temperature for each fuel blend with and without the aid of fuel delivery devices.

Fuel blends to be used:

	PROPANE (%)	PROPYLENE (%)	N-BUTANE (%)	ISO-BUTANE (%)
GRADE 1	92.5	5	2.5	0
BLEND 1	75	5	10	10
BLEND 2	55	5	20	20

Other fuel blends could also be tested with higher butane contents, with different percentages of N-Butane and Iso-Butane, or with small percentages of Ethane, etc.

* Spark advance may have to be retarded with higher butane content fuel blends to avoid detonation.

SECTION	DEVELOPMENT GROUP	OBJECTIVES: Maximum Commercial Use of LPG	OBJECTIVES: Maximum Non-Commercial Use of LPG
10.1	Compression Ratio Development	B	B
10.2	Carburetion Development - F/A Ratio Control	A/B*	A/B*
10.3	Carburetion Development - F/A Distribution	C	C
10.4	Carburetion Development - Vaporizer Sludge Formation	B	B
10.5	Ignition System Development - Spark Plug Heat Range	D	D
10.6	Ignition System Development - Voltage Requirements	D	D
10.7	Valve Timing Development	D	D
10.8	Engine Durability Development - Valves & Valve Seats	A	A
10.9	Ergine Durability Development - Piston Rings	C	C
10.10	Engine Durability Development - General Engine Durability	C	C
10.11	Engine Oil Development	B	B
10.12	Fuel Systems Development - Container Shapes & Materials (Feasibility Study only)	B/C*	B/C*
10.13	Fuel Systems Development - Corrosion	B	B
10.14	Fuel Systems Development - Refueling Hardware	A	A
10.15	Fuel Systems Development - Automatic Stop-Fill Systems	A	A
10.16	Fuel System Development - Welding Slag and Debris in Tanks	B	B
10.17	Dual-Fuel - Compression Ratio Development	B/D*	A/B*
10.18	Dual-Fuel - Ignition System Development		
10.19	Dual-Fuel - Hardware Development 1		
10.20	Dual-Fuel - Hardware Development 2		
10.21	Low Temperature Operation - Vaporizer Development	A	A
10.22	Low Temperature Operation - Cold Cranking and Starting	B	B
10.23	Fuel Blends	B	B

* X/Y Rating = Cars and Trucks under 2200 kg GVWR except RWD / Trucks 2200 kg to 4500 kg GVWR

TABLE 10 R & D PROGRAM PRIORITIES

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